

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau



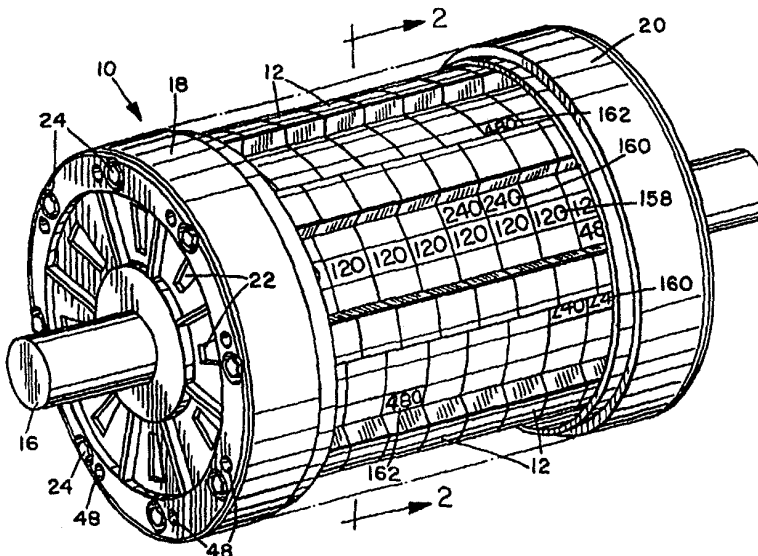
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶ : H02K 21/24, 3/26, 3/04		A2	(11) International Publication Number: WO 98/26495
			(43) International Publication Date: 18 June 1998 (18.06.98)
(21) International Application Number: PCT/US97/22555		(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).	
(22) International Filing Date: 8 December 1997 (08.12.97)			
(30) Priority Data: 08/763,824 11 December 1996 (11.12.96) US			
(71) Applicant (for all designated States except US): ADVANCED TECHNOLOGIES INTERNATIONAL, LTD. [BS/BS]; Unwala House, East Street North, P.O. Box N-8097, Nassau (BS).			
(72) Inventors; and (75) Inventors/Applicants (for US only): SMITH, Stephen, H. [US/US]; 407 Parkwood Lane, Leucadia, CA 92024 (US). SHENKAL, Yuval [US/US]; 2235 Montgomery Avenue, Cardiff, CA 92007 (US).			
(74) Agents: HALLER, John, L. et al.; Brown, Martin, Haller & McClain, 1660 Union Street, San Diego, CA 92101-2926 (US).		Published Without international search report and to be republished upon receipt of that report.	

(54) Title: MOTOR/GENERATOR

(57) Abstract

An axial field motor/generator having a rotor that includes at least three annular discs magnetized to provide multiple sector-shaped poles. Each sector has a polarity opposite that of an adjacent sector, and each sector is polarized through the thickness of the disc. The poles of each magnet are aligned with opposite poles of each adjacent magnet. Metal members adjacent the outermost two magnets contain the flux. The motor/generator also has a stator that includes a stator assembly between each two adjacent magnets. Each stator assembly includes one or more conductors or windings. Although the conductors may be formed of wire having a round, uniform cross section, they may alternatively be formed of conductors having a tapered cross section that corresponds to the taper of the sectors in order to maximise the density of the conductor in the gap between axially adjacent poles. The conductors may also alternatively be formed of traces in a printed circuit, which may have one or more layers. Each stator assembly may be removably connectable to another stator assembly to provide modularity in manufacturing and to facilitate selection of the voltage at which the motor/generator is to operate. Electrical contacts, such as pins extending from the casing, may removably connect the conductors of adjacent stator assemblies. A magnet may be dynamically balanced on the shaft by hardening a thin ring of cross-linked resin between the magnet and the shaft while the shaft is spun, using ultraviolet light to polymerize the resin.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

-1-

MOTOR/GENERATOR**BACKGROUND OF THE INVENTION**5 1. Field of the Invention

The present invention relates generally to electric motor/generators and, more specifically, to a permanent magnet, axial field motor/generator.

10 2. Description of the Related Art

10 An electric motor, which is a machine for converting current into motion, typically includes a rotor that rotates within a stator in response to a magnetic field. In a permanent magnet motor, the rotor or stator, typically the stator, includes one or more permanent magnets that generate a magnetic field. Permanent magnets may be made of ferrous metals or
15 ferroceramic materials. Because the machine may also be used to convert motion into electric current, the machine is often referred to in the art as a motor/generator or a dynamo. Therefore, although the term "motor" is used herein for convenience, it should be understood that the same machine may be used as a generator.

20 The rotor or stator of a permanent magnet motor, typically the rotor, includes conductors, such as copper wire, wound around a form. These windings typically have numerous turns of the wire in order to maximize the magnitude of the magnetic field.

25 In certain permanent magnet motors, the stator includes a metal casing that holds two or more magnets and completes the magnetic circuit between them. The casing typically comprises metal plates or laminations to minimize eddy currents. Increasing the amount of metal in the casing lowers the reluctance of the circuit, thereby increasing the proportion of magnetic flux in the gaps between the magnet poles through which the rotor
30 windings move.

Common motor magnet materials include iron, an aluminum-nickel-cobalt alloy known as Alnico, and rare-earth materials, such as a samarium-cobalt alloy. These materials provide a strong magnetic field but are quite heavy.

35 Motor magnets commonly must be magnetized in-place, i.e., after they have been assembled into the metal motor casing, to minimize

-2-

demagnetization upon assembly. If a magnet is removed from the casing (or inserted into it), the act of removing (or inserting) it generally demagnetizes it to some extent. Replacing the magnet would result in diminished performance. To minimize demagnetization, a metal "keeper" may temporarily be attached to a magnet prior to mounting it in a motor or other device.

Practitioners in the art have developed axial field motors having magnets disposed on a rotor with their fields aligned parallel to the axis of rotation of the motor. Axial field motors do not require heavy metal casings to contain the field. Practitioners in the art have developed small axial field motors that include economical ferroc ceramic magnets. Unlike rare earth magnets, ferroc ceramic magnets can readily be magnetized into multiple poles because they have a relative permeability (" μ ") on the order of 1. (Permeability is defined as the ratio between the magnetic field density (B) of a material to its magnetic field intensity (H). Air, by definition, has a relative permeability of 1.) In certain such motors, each rotor disc is magnetized into multiple sector-shaped poles. Each sector has a polarity opposite that of an adjacent sector, and each sector is polarized through the thickness of the disc. The rotor is disposed adjacent to the stator on a common axis. The stator of such a motor typically consists of multiple toroidal windings. The magnetic field through which the windings pass is concentrated between two adjacent sectors of the same disc.

Motors having ferroc ceramic magnets produce lower torque than motors having magnets made of high-permeability materials, such as iron, Alnico and rare earth materials, because ferroc ceramic magnets exhibit a lower flux density. To obtain an increase in torque, the rotor may have two disc magnets, one on each side of the stator. Half of each toroidal winding of the stator thus passes through the magnetic field generated by one magnet of the rotor, and the other half of the winding passes through the magnetic field generated by the other rotor magnet. Nevertheless, the density of the flux through which each winding half moves is limited to that produced by the disc magnet to which it is closest. The use of multiple pole ferroc ceramic magnets is therefore largely confined to small, low-torque motors, such as stepper-type motors used in disk drives.

-3-

It would be desirable to provide an economical motor that has a high power-to-weight or efficiency ratio. These needs are clearly expressed in the art and are satisfied by the present invention in the manner described below.

5

SUMMARY OF THE INVENTION

The present invention pertains to an axial field motor/generator having a rotor that includes at least three annular discs magnetized to provide multiple sector-shaped poles. Each sector has a polarity opposite that of an adjacent sector, and each sector is polarized through the thickness of the disc. These magnets may be made of any suitable, relatively low magnetic permeability (" μ ") material, such as a ferroceramic material having a permeability of no more than about 100 times the permeability of air. The poles of each magnet are aligned with opposite poles of each adjacent magnet. The magnetic flux thus is oriented axially through aligned sectors of adjacent magnets. Metal members adjacent to the outermost two magnets contain the flux in the rotor. Thus, conceptually, the flux follows a circular serpentine path through and around the rotor.

The magnets are polarized into a plurality of sectors, which minimizes demagnetization prior to assembly of the rotor. Thus, the magnets need not be magnetized in-place, i.e., after assembly, as in certain conventional motors. Moreover, it is not necessary to use a keeper tool to maintain magnetization during assembly.

The motor/generator also has a stator that includes a layer of conductors or windings between each two adjacent rotor magnets. Each layer may have multiple conductor phase assemblies, each providing one of a plurality of phases. Although the conductors may be formed of conventional wire having a round, uniform cross-section, they may alternatively be formed of conductors having a tapered cross-section that corresponds to the taper of the sectors. This type of cross-section maximizes the density of the conductor in the gap between axially adjacent poles and, thus, the current capacity of the conductor. The cross-sectional shape may be rectangular to further maximize conductor density.

The terms "rotor" and "stator," as defined herein, are used for purposes of convenience to mean only that the rotor and stator rotate with respect to one another. The terms are not intended to limit the invention to a structure

-4-

in which the rotor rotates and the stator is stationary with respect to the earth or other frame of reference. For example, the rotor may be fixedly connected to a vehicle body, and the stator may be fixedly connected at its periphery to a tire, whereby the rotation of the stator and its tire relative to the rotor and the vehicle body propels the vehicle.

Although the magnets do not have as high a magnetic flux density ("B") as rare earth magnets and other high-permeability magnets, they have a higher maximum energy product. Energy product is the product of flux density and magnetization force or coercivity ("H") at the point along the magnet's characteristic B-H plot at which the motor/generator is operating. The magnets are thus preferably spaced apart from one another by a distance corresponding to the maximum energy product.

The inclusion of three or more rotor magnets in the manner described above more than offsets the negative effect of lower flux density on motor efficiency. Each point or magnetic domain within each center magnet, i.e., a magnet other than the two outer magnets, contributes equally to the magnetic flux through which the stator conductors pass. Flux emanating from domains immediately to either side of the midplane of a center magnet thus has a shorter gap to traverse than flux emanating from corresponding domains in a conventional axial field motor. In other words, both "sides" of each center magnet contribute to the total flux interacting with a stator conductor. Using both sides of the magnet in this manner produces a high average energy product.

Each layer of the stator may be removably connectable to another layer to provide modularity in manufacturing and to facilitate selection of the voltage at which the motor/generator is to operate. Each layer may include a casing in which the conductors are enclosed or embedded. Electrical contacts, such as pins extending from the casing, removably connect the conductors of adjacent layers. Because voltage is dependent upon the length of a conductor that passes through a magnetic field, selecting the total conductor length of each phase selects the voltage. The pins or other electrical contacts may be disposed around the casing in a manner that allows a user or manufacturer to select the operating voltage of the motor/generator by connecting adjacent layers in a selected angular orientation with respect to each another. If the user or manufacturer selects an orientation in which the conductors of adjacent layers are electrically

-5-

connected in parallel, the operating voltage will be lower than if the user or manufacturer selects an orientation in which the conductors of adjacent layers are electrically connected in series. Thus, the user or manufacturer may connect the casings in various combinations of angular orientations to select one of a number of voltages at which the motor/generator is to operate, such as 120 volts, 240 volts and 480 volts. The exteriors of the casings may be marked with indicia that facilitate the selection of an operating voltage by aligning the indicia and then connecting the casings via the pins.

5 The present invention also includes a novel method that may be used to mount the magnets during manufacture of the motor. In accordance with this method, a magnet is dynamically balanced on the shaft on which it is mounted by hardening a thin ring of liquid material between the magnet and the shaft (or a hub mounted to the shaft) while the shaft is spun. The material may be, for example, a polymer resin that is cross-linked and thus hardened by exposure to ultraviolet light while the shaft is spun.

10 The foregoing, together with other features and advantages of the present invention, will become more apparent when referring to the following specification, claims, and accompanying drawings.

20

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, reference is now made to the following detailed description of the embodiments illustrated in the accompanying drawings, wherein:

25 Figure 1 is a pictorial view of an exemplary motor/generator of the present invention;

Figure 2 is an enlarged sectional view taken on line 2-2 of Fig. 1;

Figure 3 is a sectional view taken on line 3-3 of Fig. 2;

30 Figure 4 is a face view of a rotor of the motor/generator, showing the polarization of the magnet;

Figure 5 is a side elevation view of a rotor;

Figure 6 is a graphical illustration of the magnetic flux emanating from a rotor;

35 Figure 7 is a plot of magnetic flux of the magnetic flux versus the coercivity of a magnet;

-6-

Figure 8 is a plot similar to Fig. 9, showing magnetic flux versus coercivity of a magnet of the motor/generator;

Figure 9 is a pictorial view of a method for assembling a rotor by mounting a magnet on a hub;

5 Figure 10 is a pictorial view of a method for curing the material that adheres the magnet to the hub;

Figure 11 is a pictorial view of a stator of the motor/generator;

Figure 12 illustrates a stator winding arrangement having multiple turns of wire conductors;

10 Figure 13 is a schematic diagram of the stator winding arrangement;

Figure 14 is a pictorial view of an alternative stator winding arrangement having single-turn, rectangular cross-section conductors;

Figure 15 is a flux diagram of the rotor;

15 Figure 16 is a top plan view of a portion of another alternative stator winding arrangement having multiple laminations of two-sided, flexible, printed circuit material, showing the portion of the stator winding arrangement relating to one phase of windings of one of the laminations;

Figure 17 is a top plan view similar to Fig. 15, but illustrating both sides of one of the laminations;

20 Figure 18 is a sectional view taken along line 18-18 of Fig. 17, showing the multiple laminations;

Figure 19 is a sectional view taken along line 19-19 of Fig. 17;

25 Figure 20 is a partial top plan view similar to Fig. 17, but showing the portion of the stator winding arrangement relating to 12 phases of windings of one of the laminations;

Figure 21 is a block diagram of a motor controller;

Figure 22 is a timing diagram of the motor signals;

30 Figure 23 is a schematic diagram of the stators connected to one another in a configuration selected to operate the motor/generator at a first voltage;

Figure 24 is a schematic diagram of the stators connected to one another in a configuration selected to operate the motor/generator at a second voltage;

35 Figure 25 is a schematic diagram of the stators connected in a configuration selected to operate the motor/generator at a third voltage; and

-7-

Figure 26 is, in part, a front elevation view of a vehicle having the motor/generator disposed within a wheel and, in part, a cross-sectional detail view of an alternative embodiment of the motor/generator suitable for installation within the wheel.

5

DESCRIPTION OF PREFERRED EMBODIMENTS

As illustrated in Figs. 1-3, a motor/generator includes a housing 10 (the center section of which is shown removed), multiple layers or stator assemblies 12 connected to one another and disposed within housing 10, and a rotor having multiple rotor discs 14 connected to a shaft 16 that extends axially through housing 10. Housing 10 includes two endpieces 18 and 20, each having multiple housing ventilation openings 22. Housing 10 also includes at least one removable midsection piece between endpieces 18 and 20 that is indicated in phantom line in Figs. 1-3 but not shown for purposes of clarity. Endpieces 18 and 20 and the removable midsection pieces are preferably made of light-weight plastic. Bolts 24 extend from endpiece 18 axially through housing 10 through each stator assembly 12 and are secured by nuts 26 at endpiece 20. At one end of housing 20, ball bearings 28 retained between a first bearing race 30 connected to shaft 16 and a second bearing race 32 connected to endpiece 18 facilitate rotation of shaft 16 with respect to housing 10. A similar bearing arrangement having ball bearings 34 retained between a first bearing race 36 connected to shaft 16 and a second bearing race 38 connected to endpiece 20 facilitate rotation of shaft 16 at the other end of housing 10.

1. Modular Construction of the Motor/Generator

Rotor discs 14 are interleaved with stator assemblies 12. Although stator assemblies 12 are described in further detail below, it should be noted that stator assemblies 12 are removably connectable to one another. A motor/generator having any selected number of stator assemblies 12 may be constructed. Stated another way, the motor/generator has a stator comprising a selected number of layers. Preferably, for reasons discussed below, the motor/generator has at least two stator assemblies 12 and three rotor disks 14. Removable pins 40 plug into sockets 42 to electrically

-8-

connect each stator assembly 12 to an adjacent stator assembly 12. Electrical power leads 44 extend into housing 10 and have plugs 46 that connect to sockets 42 in one of the two endmost stator assemblies 12. Although Fig. 3 illustrates a power lead 44 connected to the endmost stator assembly 12 adjacent endpiece 20, it could alternatively be connected to the endmost stator assembly 12 adjacent endpiece 18. As illustrated in Figs. 1 and 3, openings or ports 48 and 50 in endpieces 18 and 20, respectively, admit plugs 46 into housing 10. A sensor 52, which is preferably a Hall-effect sensor, is mounted to endpiece 20. Sensor 52 is adjacent the endmost rotor disc 14 for sensing pole transitions, as described below with respect to the operation of the motor/generator.

2. The Rotor

As illustrated in Figs. 2 and 4, each rotor disc 14 includes an annular ceramic magnet 54 mounted on a hub 56. Hub 56 has hub ventilation openings 58 with angled, vane-like walls for impelling cooling air through housing 10. Magnets 54 may be made from a suitable ferroceramic material, such as M-V through M-VIII, oriented barium ferrite ($\text{BaO} \cdot 6\text{Fe}_6\text{-O}_2$), strontium ferrite ($\text{SrO} \cdot 6\text{Fe}_6\text{-O}_2$), or lead ferrite ($\text{PbO} \cdot 6\text{Fe}_6\text{-O}_2$). Alternatively, magnets 54 may be made from a bonded neodymium material. Such materials have the added advantage of being much lighter than rare earth and iron magnetic materials. Both ferroceramic magnets and bonded neodymium magnets are known in the art and commercially available. As illustrated in Fig. 4, each magnet 54 is polarized to provide multiple sectors 57 uniformly distributed angularly around magnet 54. As illustrated in Fig. 5, each sector is polarized through the thickness of magnet 54. Thus, each sector has opposite poles on opposite faces 60 and 62 of the magnet 54. In addition, the poles of sectors 57 on face 60 alternate with those of adjacent sectors 57 on face 60, and the poles of sectors 57 on face 62 alternate with those of adjacent sectors on face 62. Each rotor disc 14 is mounted on shaft 16 with the poles of its magnet 54 axially aligned with opposite poles of an adjacent magnet 54 (i.e., a North pole on face 62 of a first rotor magnet 54 will be axially aligned with a South pole on face 60 of a second adjacent rotor magnet 54). Magnetic flux therefore exists between such axially aligned poles. As illustrated in Figs. 3 and 15, annular discs or endplates 64 and 66,

made of a suitable high-permeability material such as steel, are mounted to faces 60 of the magnets 54 of the endmost two rotor discs 14. Endplates 64 and 66 contain the magnetic flux between adjacent poles of the rotor magnet 54 adjacent to endplate 64 or 66.

5 As illustrated in Fig. 15, conceptually, the magnetic flux "flows" from a sector 57 of a first one of the two endmost magnets 54, through axially aligned sectors 57 of adjacent magnets 54 until reaching the second one of the two endmost magnets 54, where one of endplates 64 and 66 directs the flux to an angularly adjacent sector 57. The flux then returns axially through
10 aligned sectors 57 of adjacent magnets 54 until again reaching the first endmost magnet 54, where the other of endplates 64 and 66 directs the flux to an angularly adjacent sector 57. The magnets 54 other than the two endmost magnets 54 may be referred to herein for convenience as inner or center magnets 54. The flux thus follows a serpentine pattern, weaving
15 axially back and forth through aligned sectors 57 of magnets 54.

As noted above, the motor/generator should have at least one inner or center magnet 54 and two outer or endmost magnets 54. Nevertheless, the greater the number of center magnets 54, the greater the ratio of total flux density to total weight of the motor/generator and, correspondingly, the
20 greater the power-to-weight ratio of the motor/generator. Therefore, the motor/generator preferably has at least three or four center magnets 54 and can achieve a power-to-weight ratio of between about 0.1 and 1.0 horsepower per pound (HP/lb.), with a typical power-to-weight ratio of about 0.5 HP/lb. With this number of center magnets 54 it can achieve an
25 efficiency between about 88 percent and 99 percent, with a typical efficiency between 92 and 96 percent. The motor/generator can achieve the high flux density-to-weight ratio because essentially every point or magnetic domain within each center magnet 54 contributes to the total flux. Conceptually, flux emanating from a domain midway between faces 60 and
30 62 (Fig. 15) of a center magnet 54 impinges equally upon both adjacent stator assemblies 12. In a conventional axial field motor, the flux emanating from each magnet is directed to only one stator winding. Thus, in the conventional axial field motor, the domains closer to the winding contribute more flux than the domains farther from the winding.

35 Magnets 54 have more than two poles to minimize demagnetization before they are assembled into the rotor. The greater the number of poles,

-10-

the less demagnetization a magnet 54 will experience because the length of the flux lines between adjacent poles will be minimized. While it is difficult if not impossible to create pole transitions in high-permeability material, e.g., iron, steel, Alnico and samarium-cobalt materials, which have permeabilities thousands of times that of air, pole transitions are readily created in low-permeability materials, such as ferroc ceramic and bonded neodymium materials, which having permeabilities on the order of that of air. Nevertheless, any material having a permeability no more than about 100 times that of air would be suitable for magnets 54. As illustrated in Fig 6, the flux density (B) curve 68 transitions sharply at the midpoint 70 between poles of a magnet 54. In contrast, the flux density (B) curve 72 of a high-permeability magnet (not shown) would transition very gradually, thereby defining poles that are less distinct than those of a ferroc ceramic magnet. The transition area, "d", is defined as the area in which the magnetic flux emanating from a pole returns to a laterally adjacent pole on the same magnet 54 rather than travels to an axially adjacent pole of an axially adjacent magnet 54.

The number of poles in magnets 54 and the spacing between magnets 54 along rotor shaft 16 (see Fig. 15) is preferably determined in response to the magnetization characteristics of the ceramic material. As illustrated in Fig. 7, an exemplary characteristic curve, sometimes referred to as a "B-H curve" 74, is defined by a plot of flux density (B) versus coercivity (H) of magnet 54. A similar B-H exemplary curve 76 for a high-permeability magnet is shown for comparison. It should be noted that curves 74 and 76 each include two relatively flat portions of differing slopes connected at a "knee."

As illustrated in Fig. 15, and with reference to Fig. 8, the spacing 77 between adjacent magnets 54 on rotor shaft 16 is preferably selected to maximize the energy product 78, which is defined as the product of flux density and coercivity at a point on B-H curve 74. (Flux density, expressed in units of Gauss, multiplied by coercivity, expressed in units of Oersteds, is equal to energy, expressed in units of Joules.) Energy product 78 is maximized when magnets 54 operate at exemplary point 80 on B-H curve 74. Because the demagnetizing force or coercivity (H) of a magnet 54 is proportional to spacing 77, and the flux density (B) of a magnet 54 is proportional to its thickness, spacing 77 of a magnet 54 operating at point

80 can be calculated by dividing the thickness of magnet 54 by the slope of B-H curve 74 at the portion of the curve near the B axis that is relatively flat. For the preferred ferroceramic materials, the slope at this portion of their B-H curve is approximately equal to one; thus, energy product 78 is maximized when magnets 54 are spaced by a distance equal to their thickness.

Spacing 77 can also be described in relation to the width of the transition zone (d) between adjacent poles of a magnet 54. (See Fig. 6). As described above, in the transition zone, magnetic flux emanating from a pole returns to an adjacent pole on the same magnet 54 and does not travel to a pole of an adjacent magnet 54, because the length of each flux line in the transition zone is shorter than the axial distance between that point and a point on an adjacent magnet 54. Thus, the length of a flux line spanning the transition zone is essentially equal to spacing 77. Because flux lines returning to an adjacent pole of the same magnet 54 are essentially semicircular in air, the length of a flux line spanning the transition zone is equal to one-half the circumference of a circle having a diameter that is the width of the transition zone. Therefore, the width of the transition zone is twice spacing 77 divided by pi (π).

As illustrated in Fig. 4, and with reference to Fig. 8, the number of sectors 57 (or, equivalently, the number of poles) is preferably selected to operate magnets 54 exactly at the knee of their B-H curve 74, indicated by point 82, prior to assembling magnets 54 into the rotor. Because the demagnetizing force or coercivity (H) of a magnet 54 is proportional to the length of its longest flux lines, and the flux density (B) of a magnet 54 is proportional to its thickness, the length of the longest flux lines 81 of a magnet 54 operating at point 82 can be calculated by determining the slope of a diagonal 83 of a box having a corner at point 82, and then dividing the thickness of magnet 54 by this slope. The longest flux lines 81 extend between points substantially at the centers of adjacent sectors 57 at the outer peripheries of sectors 57. Because flux lines returning to an adjacent pole of the same magnet 54 are essentially semicircular in air, the distance or chord between such center points is equal to twice the length of the longest flux lines 81 divided by pi (π). (Viewed from the top, as in the plan view of Fig. 4, the longest flux lines 81 appear coextensive with such chords.) The angle 85 subtended by such a chord divided into 360 degrees is equal to the preferred number of sectors 57. The exemplary magnet 54

-12-

shown in Fig. 8 has eight sectors 57, each subtending an angle of 45 degrees.

By operating magnets 54 at the knee prior to assembly, the flux between each pole of a magnet 54 and the axially aligned pole of an adjacent magnet 54 is maximized when the rotor is assembled. A greater number of poles would increase the flux density between the angularly adjacent poles of a magnet 54 and correspondingly decrease the flux between axially adjacent magnets 54. A lesser number of poles would move the operating point beyond the knee to, for example, point 84. Once the operating point of a magnet has moved beyond the knee of its characteristic B-H curve, it becomes permanently demagnetized to some extent and thereafter operates on a minor B-H curve 86.

As illustrated in Fig. 9, a novel method may be used to mount magnets 54 to a hubs 56. As those of skill in the art will appreciate, annular ceramic magnets typically are not precisely uniform as a result of the casting and kilning method by which they are made. Thus, their centers of gravity are typically not located precisely at their centers. It is therefore desirable to balance each magnet 54 to minimize vibration and mechanical stresses during operation of the motor/generator. Nevertheless, it would be difficult to balance magnets 54 by removing material from them because ceramic materials are difficult to machine. It would also be difficult to balance magnets 54 by attaching weights or bands to their peripheries due to the differential thermal expansion between the ceramic and the weights. In accordance with the novel method, hub 56 is removably mounted on a shaft 88 connected to a motor 90. Cross-linkable polymer resin, such as the well-known type that is commercially available for dental repair, is applied to either the outer rim 92 of hub 56, the inner rim 94 of magnet 54, or both. Magnet 54 is then fit onto hub 56. Motor 90 is energized to slowly increase its speed. Hub 56 rotates magnet 54 because the relatively high viscosity of the resin creates sufficient friction or adhesion between them. The rotation dynamically balances magnet 54 on hub 56 because the resin flows and redistributes itself in the space between hub 56 and magnet 54. As illustrated in Fig. 10, when magnet 54 is rotating smoothly with no noticeable vibration, an ultraviolet lamp 96 is energized to illuminate the resin. As is well-known in the art, ultraviolet light cross-links the polymer molecules and thereby hardens the resin. Magnet 54 remains balanced while

-13-

the resin hardens because it remains spinning with hub 56. When the resin is sufficiently hardened, lamp 76 and motor 70 are de-energized. The resulting rotor disc 14, comprising magnet 54 adhered to hub 56 by a layer of hardened resin 98, is then removed from shaft 68.

5

3. The Stator

As described above, the stator of the motor/generator includes multiple stator assemblies 12. As best illustrated in Figs. 3, 11 and 12, one embodiment of a stator assembly 12 includes windings 100 around a dielectric form 102 that is embedded, molded or similarly encased in a substantially annular stator casing 104 made of a suitable dielectric material. Stator assembly 12 has bores 106 through which bolts 24 may be extended to physically interconnect them, as described above with respect to Figs. 1 and 2. As similarly described above, stator assembly 12 has sockets 42 that may be electrically interconnected by removable pins 40. Stator casing 104 has a central opening 108 through which shaft 16 extends when the motor/generator is assembled, as illustrated in Fig. 2. The diameter of shaft 16 is less than that of central opening 108 to facilitate airflow through the motor/generator.

As illustrated in Fig. 13, the exemplary motor/generator has four phases, designated phase-1 (ϕ_1), phase-2 (ϕ_2), phase-3 (ϕ_3) and phase-4 (ϕ_4). Each phase is defined by a conductor phase assembly, comprising a length of a suitable conductor 110, 112, 114 and 116, respectively, such as dielectric-coated copper or aluminum magnet wire of a suitable gauge, electrically connected at each end to a socket 42. For example, conductor 110 is connected between a socket 42, designated phase-1 positive ($\phi_1 +$) and a socket 42 designated phase-1 negative ($\phi_1 -$).

Although a motor/generator having four phases is illustrated, the number of phases is preferably selected in response to the length of the transition area between the poles of magnet 54. Referring briefly to Fig. 6, the motor/generator preferably has a number of phases equal to the length ("L") of the outer periphery of a sector 57 divided by the length ("d") of the

$$\text{phases} = \frac{2\pi r}{d * N}$$

-14-

transition area. The number of phases is, in effect, the number of transition areas that fit within a sector 57. If magnets 54 are spaced by the preferred distance of twice the length ("d") of the transition zone between poles, as described above with respect to Fig. 6, the preferred number of phases is:
5 where " $2\pi r$ " is the circumference of magnet 54, and "N" is the number of sectors 57.

Each conductor phase assembly includes eight windings 100 distributed around form 102. As defined herein, the term "winding" broadly refers to a conductor having at least one portion oriented or elongated in a
10 direction that traverses or cuts the flux lines when the motor/generator is in operation. Figure 13 illustrates windings 100 having one such elongated conductor portion 118 that extends from the periphery of the conductor phase assembly toward the interior of the conductor phase assembly and another such elongated conductor portion 119 that returns from the interior
15 of the conductor phase assembly to the periphery. Nevertheless, each winding 100 preferably comprises at least two turns. As used herein, a "turn" is defined as a portion of a conductor that extends from the periphery of the conductor phase assembly toward the interior and returns from the interior to the periphery. As those of skill in the art will understand, the
20 number of turns depends upon the selected voltage and current operating parameters. For purposes of clarity, however, two of the turns of each winding 100 of conductor 110 are shown in Fig. 12.

Form 102 has 32 sector-shaped or wedge-shaped partitions 120. Each group of four adjacent partitions 120 corresponds in size to a sector 57
25 of magnet 54 (Fig. 4). The turns of each winding 100 are wound around such a group of four adjacent partitions 120, and then an equal number of turns are wound around an adjacent group of four adjacent partitions 120. In this manner, the conductor is wound around each of eight groups of four partitions 120. Each of conductors 110, 112, 114 and 116 is wound in this
30 manner. The windings of conductor 110 are offset by one partition 120 from the windings of conductor 112; the windings of conductor 112 are offset by one partition 120 from the windings of conductor 114; and the windings of conductor 114 are offset by one partition 120 from the windings of conductor 116. The completed four phases of windings define a generally
35 planar or wheel-like structure on the surface of form 102, with a total of 32

-15-

elongated conductor portions 118 and 119, each consisting of a bunch or group of wires, arranged in a spoke-like manner.

As illustrated in Fig. 14, in an alternative embodiment, each of four dielectric-coated conductors 122, 124, 126 and 128, defining phases 1-4, respectively, has a rectangular cross-sectional shape. Thus, the cross-section of each of conductors 122, 124, 126 and 128 has a width and a thickness. Although in both this embodiment and the embodiment described above, the windings are electrically connected in the manner schematically illustrated in Fig. 13, in this embodiment the windings are also physically arranged in a manner similar to that illustrated in Fig. 13. In other words, each of conductors 122, 124, 126 and 128 has eight windings, each having exactly one turn, and each offset from an adjacent winding by four conductor widths. The windings of conductor 122 are offset by one conductor width from the windings of conductor 124; the windings of conductor 124 are offset by one conductor width from the windings of conductor 126; and the windings of conductor 126 are offset by one conductor width from the windings of conductor 128. The arrangement is thus analogous to that of the embodiment described above. The four phases of windings define a generally planar or wheel-like structure, with a total of 32 elongated conductor portions arranged in a spoke-like manner.

The elongated portions of conductors 122, 124, 126 and 128 are tapered or wedge-shaped, i.e., their widths decrease in a radially inward direction, thereby allowing them to be packed closely together in the spoke-like arrangement. Conductors 122, 124, 126 and 128 are preferably made of metal cast or otherwise formed into the illustrated winding shape, but it may also be suitable to wind rectangular or square tapered metal wire into the illustrated winding shape. Packing conductors 122, 124, 126 and 128 closely together maximizes the amount of their conductive material that passes through the flux. The ratio of this amount to the total amount of conductive material in the windings of a motor/generator is commonly known as the "fill factor." The fill factor for the stator shown in Fig. 14 is greater than 80 percent. Although the lengths of conductors 122, 124, 126 and 128 are less than the lengths of conductors 110, 112, 114 and 116 in the embodiment described with respect to Fig. 12, the fill factor is much greater in this embodiment. Furthermore, although the cross-sectional area of the wedge-shaped elongated portions of conductors 122, 124, 126 and 128

-16-

varies, the average cross-sectional area determines the current capacity. Thus, the minimum width of conductors 122, 124, 126 and 128 does not directly limit their current capacity.

5 In another alternative embodiment of the stator, each stator assembly comprises multiple layers or laminations, each preferably formed of printed circuit material that has been suitably etched to form the conductor pattern and electrical interconnections between layers described below. The printed circuit material and etching process may be any such material and process known in the art that is commonly used to manufacture printed circuit boards
10 or flexible printed circuits in the electronics industry. The laminations or layers are bonded together or otherwise attached to one another. The resulting multiple-layer printed circuit stator assembly functions in the same manner as stator assembly 12, described above with respect to other embodiments. In that regard, this alternative stator assembly may have any
15 suitable number of phases and any suitable number of windings per phase. The alternative stator assembly may have a thickness as small as about 0.1 inches, thereby facilitating the construction of smaller motor/generators. Nevertheless, a typical alternative stator assembly for a small motor may have a thickness of about 0.25 inches. Larger motors may be constructed
20 using an alternative stator assembly having a thickness as great as about two inches.

As illustrated in Fig. 16, each layer or lamination of the alternative stator assembly comprises a substrate 129 made of a suitable dielectric material and multiple arms 131 made of metal that remains following the
25 etching or other manufacturing process. The ellipsis ("...") between arms 131 indicates that additional arms 131 are included, as described below, but are not shown in Fig. 16 for purposes of clarity. A preferred printed circuit material is a flexible plastic material, commonly referred to as "flex PC," in which substrate 129 is a thin sheet-like plastic to which is bonded a thin
30 layer of copper. Substrate 129 is preferably less than about .010 inches (10 mils) thick, and arms 131 are preferably less than about .005 inches (five mils) thick. Printed circuit material having a four mil copper layer has been used. The pattern of arms 131 is formed using photolithographic methods well-known in the printed circuit board fabrication industry. Each arm 131
35 is oriented in a substantially radial direction with respect to an axis 133 normal to substrate 129. Each arm 131 has an elongated conductor portion

-17-

135 that is oriented in a radial direction so that a current is induced as it moves through the lines of magnetic flux when the motor/generator is assembled.

As illustrated in Figs. 17 and 18, each layer or lamination preferably has arms on both sides, in the manner associated with what is commonly known as a two-sided printed circuit board. In Fig. 17, arms 131 on the first side are shown in solid line, and arms 137 on the second side are shown in broken line. Arms 131 and 137 are essentially identical, mirroring one another in size and position. Each end of an arm 131 is electrically connected to an end of an arm 137 via an inter-side through-hole 139. Each inter-side through-hole 139 is plated on its interior to provide a conductive path in the manner well-known in multi-layer printed circuit board manufacture.

A first terminal through-hole 141 is disposed at one end of one of arms 131, and a second terminal through-hole 143 is disposed at one end of another of arms 131. Terminal through-holes 141 and 143 are plated through-holes similar to inter-side through-holes 139, but they do not connect an arm 131 to an arm 137. Rather, terminal through-holes 141 and 143 form the terminals of an electrical circuit. That electrical circuit is the conductor phase assembly or at least a portion of it. It should be noted that the conductor path of the circuit, a portion of which is indicated by arrows 145 in Fig. 17, begins at terminal 141, follows one of arms 131 on the first side of the lamination, changes sides via one of inter-side through-holes 139, and continues through one of arms 137 on the second side of the lamination. The portion of the conductor path indicated by arrows 145 defines a winding. (The winding has only a single turn of conductor, in a manner similar to the embodiment described above with respect to Fig. 14.) The circuit then follows a second winding by again changing sides via another of inter-side through-holes 139, and continues through another of arms 131. The circuit shown in Fig. 17 thus includes six such windings on each side of the lamination.

Although a conductor phase assembly may consist of only the windings of a single lamination, such as that shown in Fig. 17, a conductor phase assembly preferably includes windings of multiple laminations electrically connected in parallel. As illustrated in Fig. 18, the laminations are bonded together to form a stator assembly. A plastic sheet 147 between

-18-

laminations bonds the laminations together when heated and subjected to pressure, and also electrically insulates arms 137 of one lamination from arms 131 of an adjacent lamination. As illustrated in Fig. 19, terminal through-holes 141 of all laminations are electrically connected together, and terminal through-holes 143 of all laminations are electrically connected together, thereby electrically connecting the windings in parallel to form a conductor phase assembly.

As illustrated in Fig. 20, the stator assembly preferably includes multiple conductor phase assemblies. The embodiment illustrated in Fig. 20 includes 12 conductor phase assemblies, thereby providing a 12-phase stator assembly. In a 12-phase stator assembly, arms 131 and 137 are arranged at an angular spacing of 2.5 degrees. For purposes of clarity, only a portion of the stator assembly is shown in Fig. 20, illustrating the pair of terminals for phase-1, labeled " ϕ_1^+ " and " ϕ_1^- ", and the pair of terminals for phase-2, labeled " ϕ_2^+ " and " ϕ_2^- ". Nevertheless, the complete stator assembly has 12 pairs of terminals for phases 1-12. To electrically insulate them, arms 131 are separated from one another, and arms 137 are separated from one another, by a small spacing, which is not shown as such in Fig. 20, but rather is represented by the boundary line between adjacent arms 131 and 137 for purposes of clarity.

In view of the embodiments illustrated in Figs. 12, 14 and 16-20, persons of skill in the art will understand that in other embodiments the conductors may have any suitable size, shape, and number of windings and turns. For example, in an embodiment similar to that illustrated in Fig. 14, each winding may have two turns of rectangular wire having wedge-shaped elongated portions. A conductor may range in size among various embodiments from, for example, a thin printed circuit trace to a thick metal casting.

4. Controlling the Motor/Generator

As illustrated in Fig. 21, the motor/generator may be configured as a motor by connecting a brushless motor controller 130 of essentially conventional design. Brushless motor controller 130 receives a pole sense signal 132 from sensor 52 (Fig. 3) and generates signals 134 (ϕ_1^-), 136 (ϕ_1^+), 138 (ϕ_2^-), 140 (ϕ_2^+), 142 (ϕ_3^-), 144 (ϕ_3^+), 146 (ϕ_4^-) and 148

-19-

($\phi_4 +$). Signals 134, 136, 138, 140, 142, 144, 146 and 148 are coupled to electrical leads 44, as described above with respect to Fig. 2.

As illustrated in the timing diagram of Fig. 22, the differential voltage between signals 134 and 136 defines a series of phase-1 pulses 150; the differential voltage between signals 138 and 140 defines a series of phase-2 pulses 152; the differential voltage between signals 142 and 144 defines a series of phase-3 pulses 154; and the differential voltage between signals 146 and 148 defines a series of phase-4 pulses 156. Brushless motor controller 130 may select the width of pulses 150, 152, 154 and 156 to provide suitable motor torque. Brushless motor controller 130 sequentially generates one of pulses 150, 152, 154 and 156. Brushless motor controller 130 repeats this sequence until it receives pole sense signal 132, which indicates that magnets 54 have rotated one pole. At that point, brushless motor controller 130 reverses the voltages of pulses 150, 152, 154 and 156 but continues generating them in the same sequence.

5. Voltage Selection

The modular construction of the motor/generator facilitates selection of an operating voltage. Operating voltage is proportional to the total conductor length for each phase. Thus, an operating voltage may be selected by adjusting the total conductor length for each phase. Each stator assembly 12 has conductors 110, 112, 114 and 116, each defining one of the four phases. (See, e.g., Fig. 13.) By connecting, for example, conductor 110 in each stator assembly 12 in parallel with conductor 110 in all other stator assemblies 12, the total conductor length for phase-1 is minimized. Conversely, by connecting, for example, conductor 110 in each stator assembly 12 in series with conductor 110 in all other stator assemblies 12, the total conductor length for phase-1 is maximized. The modular construction facilitates selectably connecting the conductors of adjacent stator assemblies in either series or parallel.

As illustrated in Fig. 1, each stator assembly 12 has indicia 158, 160 and 162, such as adhesive labels, each indicating one of the voltages that may be selected. An operating voltage can be selected by connecting each stator assembly 12 in an angular orientation in which the indicia indicating a certain voltage are aligned. Indicia 158 are labeled "120" to indicate 120

-20-

volts; indicia 160 are labeled "240" to indicate 240 volts; and indicia 162 are labeled "480" to indicate 480 volts. In the exemplary relative angular orientation of stator assemblies 12 shown in Fig. 1, indicia 158 are aligned to select an operating voltage of 120 volts. To change the operating voltage, one need only uncouple one or more stator assemblies 12 and rotate them to realign indicia 158 such that they align to indicate a different operating voltage.

As illustrated schematically in Fig. 23, stator assemblies 12 are interconnected to select a first operating voltage, such as 120 volts. Broken lines indicate an electrical connection. With respect to phase-1, each end of conductor 110 in each stator assembly 12 is connected by a removable pin 40 to the corresponding end of conductor 110 in another stator assembly 12. Thus, all conductors 110 are connected in parallel. Similarly, with respect to phase-2, each end of conductor 112 in each stator assembly 12 is connected by a removable pin 40 to the corresponding end of conductor 112 in another stator assembly 12. Thus, all conductors 112 are connected in parallel. All conductors 114 and 116 are similarly connected in parallel. Pins 40 at one of the endmost stator assemblies 12 may be connected to electrical power leads 44 (Fig. 1). It should be noted that all indicia 158 are aligned, but indicia 160 and indicia 162 are not aligned.

As illustrated schematically in Fig. 24, stator assemblies 12 are interconnected to select a second operating voltage, such as 480 volts. As in Fig. 24, broken lines indicate an electrical connection. With respect to phase-1, with the exception of the two endmost stator assemblies 12, a first end of conductor 110 in each stator assembly 12 is connected by a removable pin 40 to a second end of conductor 110 in another stator assembly 12. Thus, all conductors 110 are connected in series. Similarly, with respect to phase-2, with the exception of the two endmost stator assemblies 12, a first end of conductor 112 in each stator assembly 12 is connected by a removable pin 40 to a second end of conductor 112 in another stator assembly 12. Thus, all conductors 112 are connected in series. All conductors 114 and 116 are similarly connected in series. Pins 40 at the endmost stator assemblies 12 may be connected to electrical power leads 44 (Fig. 1). It should be noted that all indicia 162 are aligned, but indicia 158 and indicia 160 are not aligned.

-21-

As illustrated schematically in Fig. 25, stator assemblies 12 are interconnected to select a third operating voltage, such as 240 volts. In the same manner as in Figs. 23 and 24, broken lines indicate an electrical connection. With respect to phase-1, with the exception of the two endmost stator assemblies 12, the corresponding first and second ends of conductors 110 in two adjacent stator assemblies 12 are connected to each other by a removable pin 40; a first end of conductor 110 in one of those stator assemblies 12 is connected by a removable pin 40 to a second end of conductor 110 in a third stator assembly 12; and the corresponding first and second ends of conductors 110 in the third stator assembly 12 and an adjacent fourth stator assembly 12 are connected to each other by a removable pin 40. Thus, groups of two conductors 110 are connected in parallel, and the groups are connected in series. Similarly, with respect to phase-2, with the exception of the two endmost stator assemblies 12, the corresponding first and second ends of conductors 112 in two adjacent stator assemblies 12 are connected to each other by a removable pin 40; a first end of conductor 112 in one of those stator assemblies 12 is connected by a removable pin 40 to a second end of conductor 112 in a third stator assembly 12; and the corresponding first and second ends of conductors 112 in the third stator assembly 12 and an adjacent fourth stator assembly 12 are connected to each other by a removable pin 40. Thus, groups of two conductors 112 are connected in parallel, and the groups are connected in series. All conductors 114 and 116 are similarly connected in parallel groups of two that are connected in series. Pins 40 at the endmost stator assemblies 12 may be connected to electrical power leads 44 (Fig. 1). It should be noted that all indicia 160 are aligned, but indicia 158 and indicia 162 are not aligned.

As persons of skill in the art will appreciate, the conductors may be interconnected in various combinations of series and parallel groups to provide more than three selectable voltages. Moreover, the illustrated set of voltages is exemplary only; in view of the teachings herein, persons of skill in the art will readily be capable of constructing a motor/generator operable at other voltages.

-22-

6. Conclusion

5 The motor/generator has a modular construction and a high power-to-weight ratio because no metal casing is required to contain the magnetic field. The field has a serpentine shape and is contained within the rotor structure by the magnets 54 themselves and two relatively small endplates 64 and 66.

10 The magnets 54 are polarized into a number of sectors 57 to minimize demagnetization prior to assembly of the rotor. Thus, the magnets 54 may be magnetized prior to assembly and maintained in inventory by the manufacturer. No keeper need be used to maintain the magnetization. Similarly, the rotor may be removed from the motor/generator to select a different operating voltage without substantially demagnetizing the magnets 54.

15 The modular construction facilitates voltage selection. To select the voltage, the orientation of each stator assembly 12 may be selected with respect to other stator assemblies 12 and then connected to other stator assemblies 12 by removable pins 40. Indicia 158, 160 and 162 on the stator assemblies 12 may aid the user in selecting the orientation.

20 The motor/generator may be used to power any suitable type of device, machine or vehicle. For example, it may be used in domestic appliances such as refrigerators and washing machines. It may also be used to power vehicles such as automobiles, trains and boats. One such use as a power plant in a vehicle is illustrated in Fig. 26. In the embodiment 25 illustrated in Fig. 25, the motor/generator is mounted in a casing 164 that functions as the hub for a traction device such as the rubber tire 166 of an automotive vehicle 168. The shaft 170 is fixedly, i.e., non-rotatably, connected to the body of vehicle 168. The rotor discs 172, which are of substantially the same construction as described above with respect to other 30 embodiments, are fixedly connected to casing 164 and thus rotate with tire 166. The stator assemblies 174 are fixedly connected to shaft 170 but are otherwise constructed as described above with respect to other embodiments. In operation, the rotation of rotor discs 172 propels the vehicle while the shaft remains stationary with respect to the ground.

35 Obviously, other embodiments and modifications of the present invention will occur readily to those of ordinary skill in the art in view of

-23-

these teachings. Therefore, this invention is to be limited only by the following claims, which include all such other embodiments and modifications when viewed in conjunction with the above specification and accompanying drawings.

5

WHAT IS CLAIMED IS:

-24-

CLAIMS

1. A motor/generator, comprising:

5 a stator having an axis and a plurality of layers spaced along said axis,
each layer including a conductor phase assembly with a winding having an
elongated conductor portion oriented in a generally radial direction with
respect to said axis;

a rotor having an axis coaxial with said stator, said rotor comprising:
a shaft rotatably coupled to said stator;

10 two annular outer magnets coaxially coupled to said shaft, each
outer magnet having a permeability, an axis, first and second faces
and a plurality of sector-shaped poles, an axial distance between said
faces defining a thickness, each pole of said first face being of
opposite polarity from a laterally adjacent pole of said first face and of
15 opposite polarity from an axially adjacent pole of said second face;

at least one annular center magnet coaxially coupled to said
shaft between said outer magnets, each center magnet having a
permeability, an axis, first and second faces and a plurality of sector-
shaped poles, an axial distance between said faces defining a
20 thickness, each pole of said first face being of opposite polarity from
a laterally adjacent pole of said first face and of opposite polarity from
an axially adjacent pole of said second face; and

one of said first and second faces of each sector of each
magnet having a pole fixedly aligned with a pole of an adjacent
25 magnet having opposite polarity; and

two endcaps, each having a permeability greater than said permeability
of said outer magnets and disposed adjacent one of said first and second
faces of an outer magnet.

30 2. The motor/generator recited in claim 1, wherein each said
conductor phase assembly comprises a plurality of planar windings angularly
distributed around said axis of said stator.

3. The motor/generator recited in claim 2, wherein each winding
35 has exactly two said elongated conductor portions.

-25-

4. The motor/generator recited in claim 1, wherein said permeability of each outer and central magnet is no more than 100 times the permeability of air.

5 5. The motor/generator recited in claim 1, wherein each magnet is made of a ferroceramic material.

6. The motor/generator recited in claim 1, wherein the thicknesses of said magnets are substantially equal, and each magnet is axially spaced
10 from an adjacent magnet by a gap spacing approximately equal to said thickness.

7. The motor/generator recited in claim 6, wherein:
flux lines having a length extend between poles of axially adjacent
15 magnets; and
the distance between corresponding center points on laterally adjacent poles of a magnet is approximately equal to twice the length of a longest one of said flux lines divided by pi.

20 8. The motor/generator recited in claim 1, wherein:
each said magnet has an opening with a circumference, and each said sector has an inside length along a portion of said circumference of said opening;
each said magnet has a transition area between poles of laterally
25 adjacent sectors, said transition area has a transition width, and each layer of said stator includes a number of said conductor phase assemblies essentially equal to said inside length divided by said transition width and multiplied by the number of sectors.

30 9. The motor/generator recited in claim 1, wherein said elongated conductor portion of each conductor phase assembly has a tapering cross-sectional area.

10. The motor/generator recited in claim 9, wherein said
35 motor/generator has a fill factor greater than 80 percent.

-26-

11. The motor/generator recited in claim 9, wherein each said elongated conductor portion has a rectangular cross-sectional shape.

12. The motor/generator recited in claim 1, wherein each elongated
5 conductor portion has a round cross-sectional shape.

13. The motor/generator recited in claim 1, wherein each said layer
of said stator comprises a plurality of laminations, each having a planar
substrate, and said winding comprises a metallic layer bonded to said
10 substrate.

14. The motor/generator recited in claim 13, wherein said substrate
is made of sheet-like plastic having a thickness less than about .025 inches.

15 15. The motor/generator recited in claim 14, wherein said winding
comprises a metallic layer having a thickness less than about .005 inches.

16. The motor/generator recited in claim 1, wherein each said layer
of said stator comprises a casing having said conductor phase assembly
20 enclosed therein.

17. The motor/generator recited in claim 16, wherein each said
casing is removably connectable to an adjacent casing.

25 18. The motor/generator recited in claim 17, further comprising a
pin extending between adjacent casings and electrically connecting said
conductor phase assemblies of said adjacent casings.

19. The motor/generator recited in claim 1, wherein said
30 motor/generator operates at an efficiency of between 88 percent and 99
percent.

20. The motor/generator recited in claim 19, wherein each magnet
is made of a ferroceramic material.

-27-

21. The motor/generator recited in claim 1, wherein said motor/generator has a power-to-weight ratio between about 0.1 to 1.0 HP/lb.

5 22. The motor/generator recited in claim 21, wherein each magnet is made of a ferroceramic material.

23. A motor/generator, comprising:

10 a stator having an axis and a conductor phase assembly, said conductor phase assembly including a winding having an elongated conductor portion oriented in a generally radial direction with respect to said axis, said elongated conductor portion having a tapering cross-sectional area; and

15 a rotor having an axis, said rotor comprising a shaft rotatably coupled to said stator and an annular magnet coaxially coupled to said shaft, said magnet having a plurality of sector-shaped poles.

24. The motor/generator recited in claim 23, wherein said stator has a fill factor greater than 80 percent.

20

25. A motor/generator, comprising:

 a stator having an axis and a plurality of layers spaced along said axis; and

25 a rotor having an axis coaxial with said stator, said rotor comprising a shaft rotatably coupled to said stator and having a plurality of magnetic fields distributed around said rotor at a plurality of angular positions, each field extending axially across at least one of said layers.

30 26. The motor/generator recited in claim 25, wherein each magnetic field is essentially confined within an axially oriented region having a sector-shaped cross-section.

27. The motor/generator recited in claim 26, wherein each layer comprises a plurality of conductor phase assemblies.

-28-

28. The motor/generator recited in claim 26, wherein each layer comprises a plurality of planar windings.

29. A method for making a motor/generator, comprising the steps
5 of:

providing a stator having an axis and a plurality of layers axially spaced along said axis, each layer including a conductor phase assembly having a plurality of planar windings angularly distributed around said axis, each winding having an elongated conductor portion oriented in a generally radial
10 direction with respect to said axis;

providing a rotor having an axis, said rotor comprising a shaft rotatably coupled to said stator; and

generating a plurality of magnetic fields distributed around said rotor at a plurality of angular positions, each field extending axially across exactly
15 one of said elongated conductor portions of each conductor phase assembly in each layer.

30. The method recited in claim 29, wherein said step of generating a magnetic field comprises generating a magnetic field essentially confined
20 within an axially oriented region of said rotor having a sector-shaped cross-section.

31. The method recited in claim 29, wherein said step of providing a stator comprises providing a stator wherein each winding has exactly two
25 elongated conductor portions.

32. The method recited in claim 29, wherein said step of providing a stator comprises providing a stator wherein each layer of said stator includes a plurality of conductor phase assemblies.
30

33. A stator for a motor/generator, comprising:
a plurality of annular casings, each enclosing a conductor phase assembly and removably connectable to an adjacent one of said annular casings along an axis, said conductor phase assembly including a winding
35 having an elongated conductor portion oriented in a generally radial direction with respect to said axis; and

-29-

a pin electrically connecting a conductor phase assembly of a casing to a conductor phase assembly of an adjacent casing.

34. The stator recited in claim 33, wherein:
5 each annular casing encloses a plurality of conductor phase assemblies; and
a plurality of said pins are disposed at equal angular spacings with respect to said axis.

10 35. A stator for a motor/generator, comprising:
a planar substrate; and
a metallic layer bonded to said substrate and defining a conductor phase assembly, said conductor phase assembly including a plurality of
15 windings angularly distributed around an axis normal to said planar substrate,
each winding having an elongated conductor portion oriented in a generally radial direction with respect to said axis.

36. The stator recited in claim 35, wherein
said planar substrate and said metallic layer bonded to said substrate
20 define a lamination; and
said stator has a plurality of said laminations attached to one another along said axis.

37. The stator recited in claim 36, wherein each winding in a
25 lamination of said plurality of laminations is aligned with a corresponding winding in all other laminations of said plurality of laminations and electrically connected to said corresponding winding.

38. The stator recited in claim 37, wherein each winding is
30 electrically connected to said conductor phase assembly in an adjacent lamination.

39. The stator recited in claim 38, wherein each winding has an
opening having a metallic wall electrically connecting said winding to a
35 corresponding winding in an adjacent lamination.

-30-

40. The stator recited in claim 36, wherein said laminations are bonded to one another.

41. The stator recited in claim 36, wherein each lamination has two sides, and has a metallic layer bonded to each of said sides.

42. The stator recited in claim 41, further comprising an insulating material between said laminations.

43. The stator recited in claim 36, wherein said planar substrate is made of sheet-like plastic having a thickness less than about ten mils.

44. The stator recited in claim 43, wherein said metallic layer has a thickness less than about five mils.

15

45. A stator for a motor/generator, comprising:

a plurality of laminations bonded to one another along an axis, each having a planar substrate normal to said axis, a first metallic layer bonded to a first side of said substrate and a second metallic layer bonded to a second side of said substrate, said metallic layers defining a conductor phase assembly, said conductor phase assembly including a plurality of windings angularly distributed around said axis, each winding having an elongated conductor portion oriented in a generally radial direction with respect to said axis; and

each winding in a lamination is axially aligned with a corresponding winding in all other laminations and electrically connected to said conductor phase assembly of an adjacent lamination.

46. The stator recited in claim 45, wherein:
said first metallic layer has a plurality of substantially radial arms not connected to one another, and said second metallic layer has a plurality of substantially radial arms not connected to one another;

each radial arm of said first metallic layer has a connection area axially aligned with a corresponding connection area of said second metallic layer and electrically connecting a radial arm of said first metallic layer to a radial arm of said second metallic layer; and

-31-

each winding comprises a radial arm of said first metallic layer and an electrically connected radial arm of said second metallic layer, wherein electrically connected and axially aligned radial arms of all said laminations together define said elongated conductor portions of said conductor phase assembly.

47. The stator recited in claim 46, wherein each radial arm has an opening having a metallic interior wall electrically connecting a radial arm of said first metallic layer to a radial arm of said second metallic layer.

48. The stator recited in claim 47, wherein said metallic interior wall of a radial arm of each lamination is electrically connected to a metallic interior wall of a radial arm of an adjacent lamination.

49. A method for manufacturing a stator for a motor/generator, comprising the steps of:

etching a sheet of printed circuit material having a substrate and a metallic layer bonded to said substrate to form a conductor phase assembly; said conductor phase assembly including a plurality of windings angularly distributed around an axis normal to said planar substrate, each winding having an elongated conductor portion oriented in a generally radial direction with respect to said axis.

50. The method for manufacturing a stator for a motor/generator recited in claim 49, wherein:

said printed circuit material has two sides, one side having a first metallic layer bonded to said substrate, and the other side having a second metallic layer bonded to said substrate; and

said etching step comprises the step of etching said first metallic layer to form a plurality of substantially radial arms not connected to one another, and etching said second metallic layer to form a plurality of substantially radial arms not connected to one another, and each radial arm of said first metallic layer has a connection area axially aligned with a corresponding connection area of said second metallic layer and electrically connecting a radial arm of said first metallic layer to a radial arm of said second metallic layer.

-32-

51. The method for manufacturing a stator for a motor/generator recited in claim 50, further comprising the steps of:

performing said etching step on a plurality of sheets of printed circuit material to form a corresponding plurality of laminations; and

5 attaching said laminations to one another along said axis such that each winding comprises a radial arm of said first metallic layer and an electrically connected radial arm of said second metallic layer, wherein electrically connected and axially aligned radial arms of all said laminations together define said elongated conductor portions of said conductor phase
10 assembly.

52. The method for manufacturing a stator for a motor/generator recited in claim 51, wherein said attaching step comprises the step of disposing an electrically insulative sheet between axially adjacent
15 laminations.

53. The method for manufacturing a stator for a motor/generator recited in claim 52, wherein said attaching step comprises the step of bonding said laminations to one another by applying heat and pressure.
20

54. A method for selecting a voltage in a motor/generator, comprising the steps of:

providing a stator comprising a plurality of annular casings, each enclosing a plurality of conductor phase assemblies and removably
25 connectable to another one of said annular casings along an axis, each annular casing having a plurality of indicia, each indicating one of a plurality of voltages and disposed at one of a plurality of angular positions on said annular casing;

disposing each casing at an angular orientation with respect to an adjacent annular casing at which said indicia of said annular casing and said adjacent annular casing indicating are aligned; and
30

electrically connecting conductor phase assemblies of said plurality of annular casings to one another.

55. The method for selecting a voltage in a motor/generator recited in claim 54, wherein said step of electrically connecting said conductor phase assemblies to one another comprises the step of coupling pins between said annular casings.

5

56. A method for making a rotor for a motor/generator, comprising the steps of:

10 providing an annular rotor disc having an opening with an inner circumference, said rotor disc capable of being magnetized such that a plurality of magnetic fields are distributed around said rotor at a plurality of angular positions, each field extending axially across a thickness of said rotor;

15 removably mounting a hub onto said shaft, said hub having an outer circumference and a shape corresponding to the inner circumference of the opening of said rotor disc;

fitting the inner circumference of the opening of said annular rotor disc onto the outer circumference of said hub;

applying a resin in between the outer circumference of said hub and the inner circumference of the opening in said rotor disc; and

20 rotating said shaft, such that said shaft causes said hub and said rotor disc to rotate, said resin flows between the outer circumference of said hub and the inner circumference of said opening of said rotor disc, and said rotor disc is dynamically balanced onto said hub.

25 57. The method recited in claim 56, wherein said rotating step further comprises the step of cross-linking said resin by exposing said resin to ultraviolet light such that said rotor disk is fixedly mounted to said hub.

30 58. The method recited in claim 57, wherein in said applying step, said resin is applied directly to the outer circumference of the opening of said rotor disc.

59. The method recited in claim 57, wherein said resin is a cross-linkable polymer.

-34-

60. The method recited in claim 59, wherein said rotating step further comprises the step of cross-linking said resin by exposing said resin to ultraviolet light such that said rotor disk is fixedly mounted to said hub.

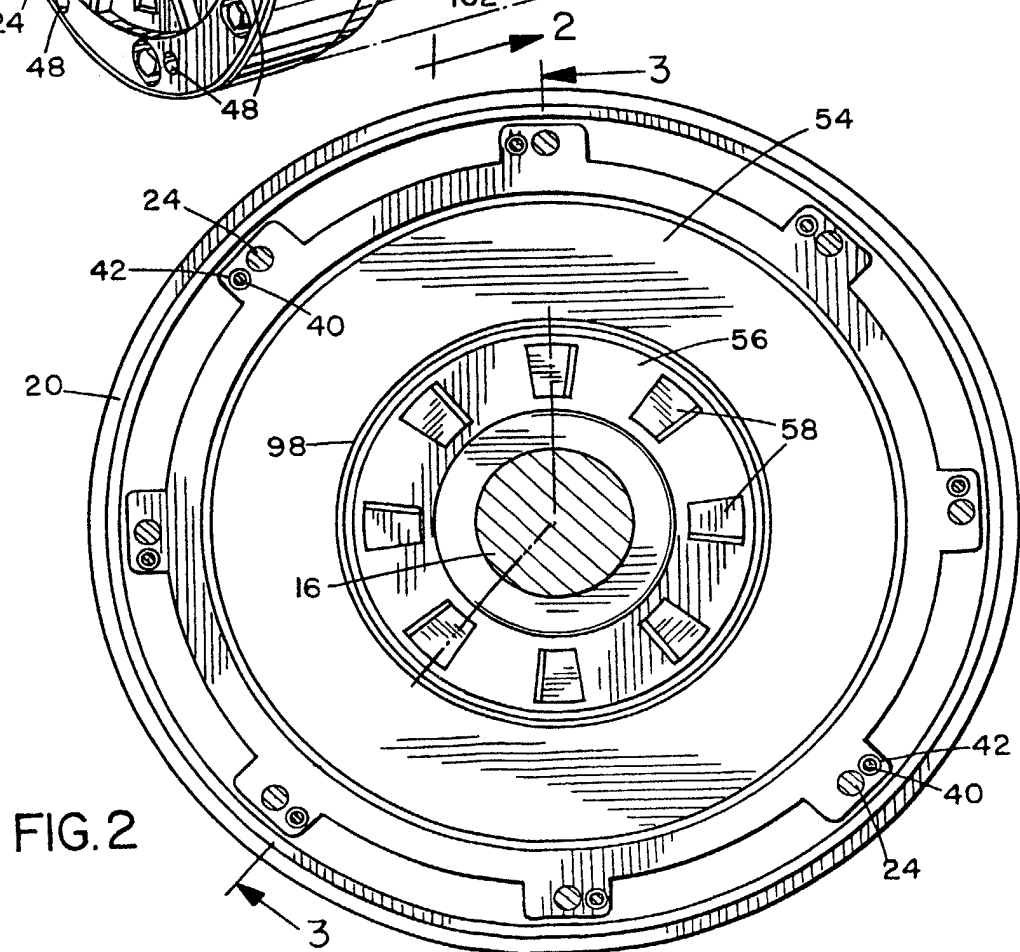
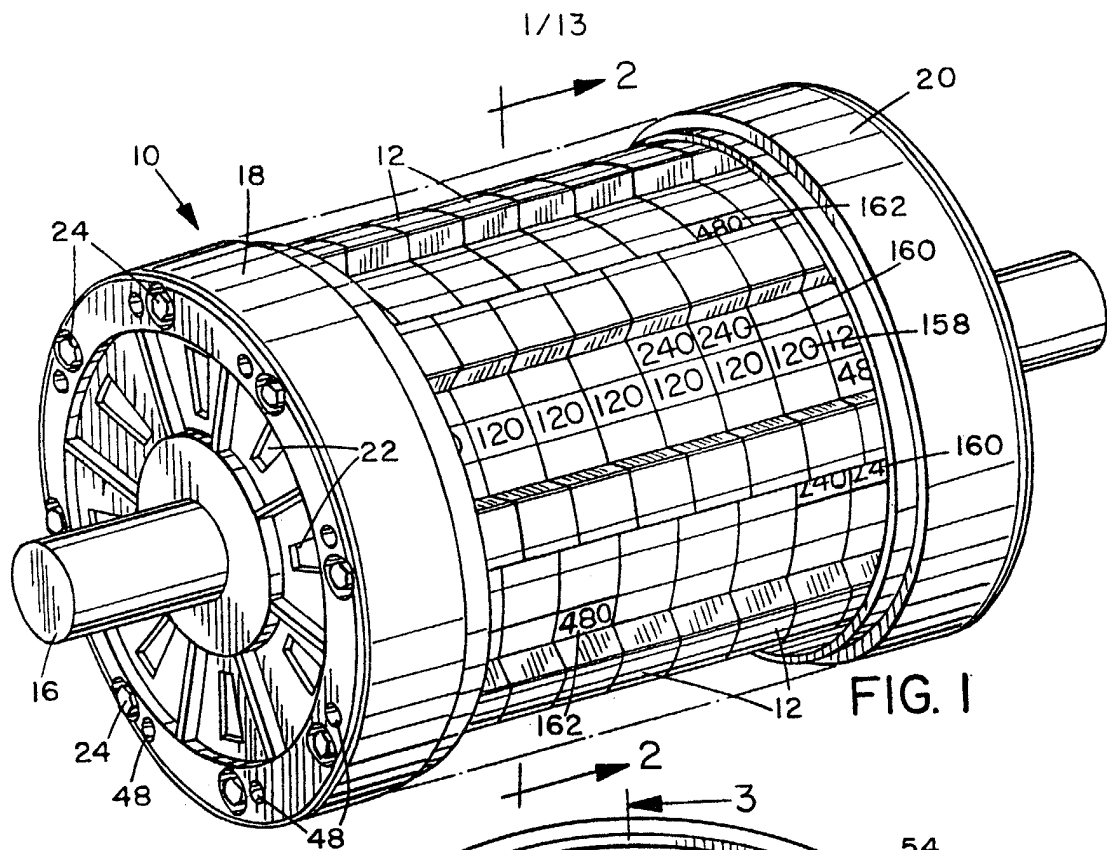
5 61. The method recited in claim 57, wherein in said applying step, said resin is applied directly to the inner circumference of the opening of said rotor disc.

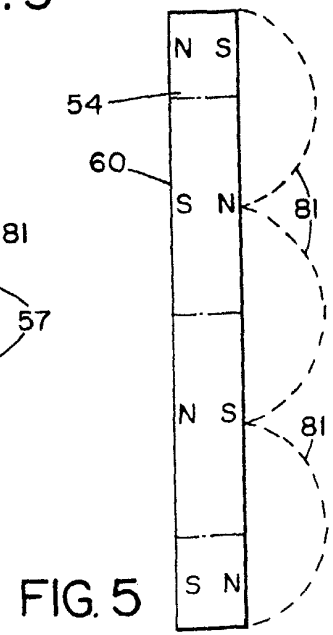
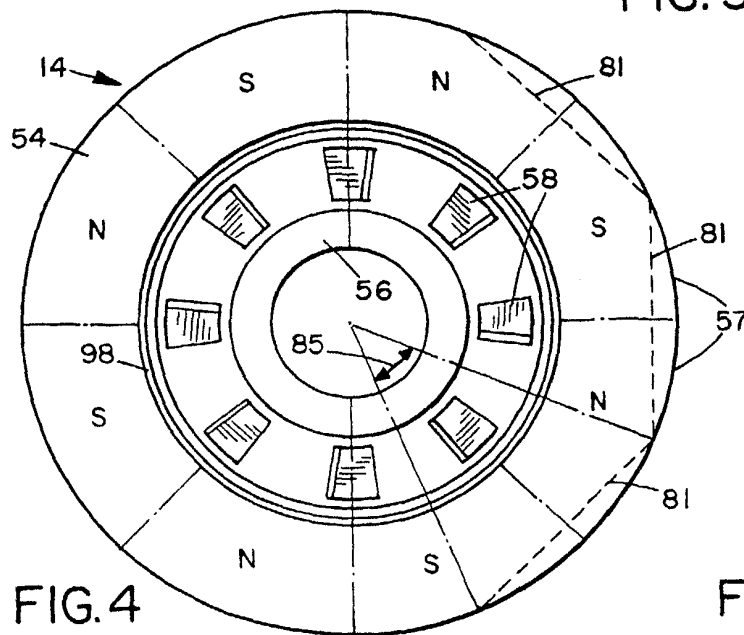
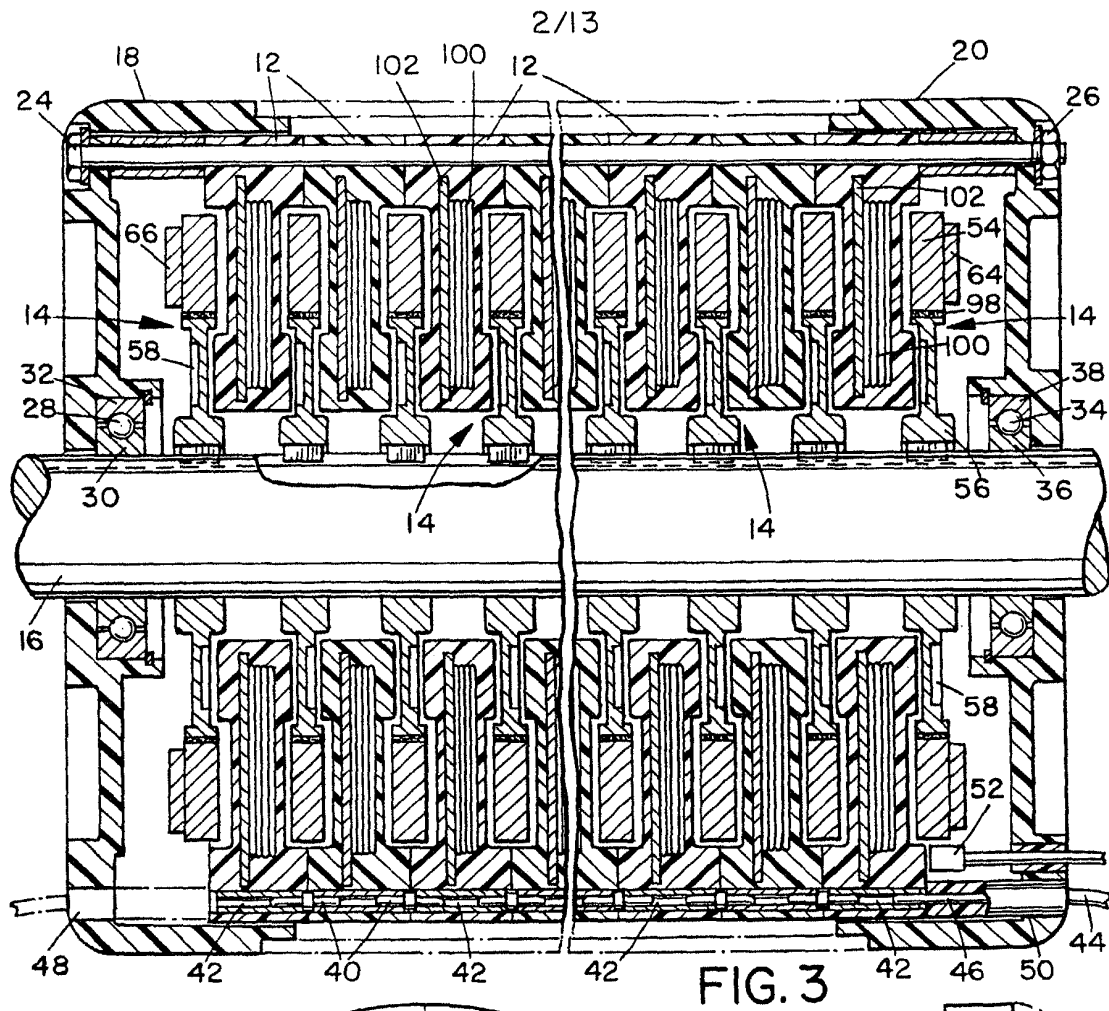
10 62. The method recited in claim 61, wherein in said applying step, said resin is further applied directly to the outer circumference of said hub.

15 63. The method recited in claim 62, wherein said rotating step further comprises the step of cross-linking said resin by exposing said resin to ultraviolet light such that said rotor disk is fixedly mounted to said hub.

20 64. A power plant for a vehicle, comprising:
a shaft fixedly connected to said vehicle;
a stator having an axis and a plurality of layers spaced along said axis and fixedly connected to said shaft, each layer having at least one
25 conductor;
a rotor having an axis coaxial with said stator, rotatably coupled to said stator, and comprising two annular outer magnets and at least one annular center magnet, each layer of said stator disposed between two magnets; and
a traction device disposed around said rotor and fixedly connected to
said rotor for gripping a surface.

65. The power plant recited in claim 64, wherein said traction device is a tire.





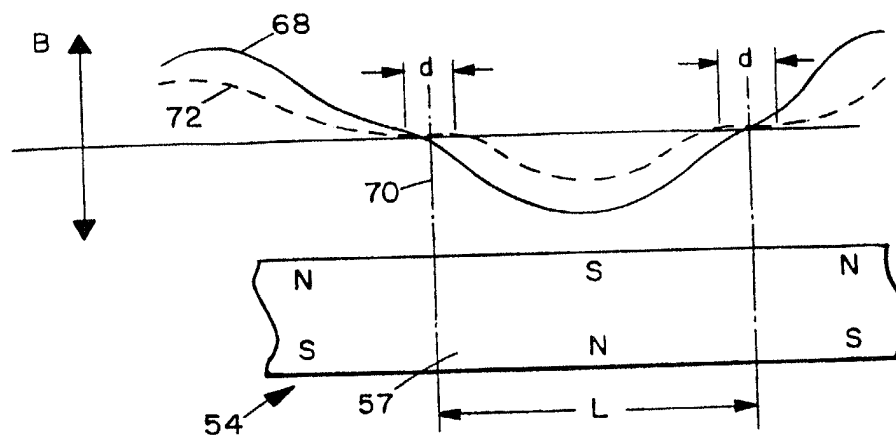


FIG. 6

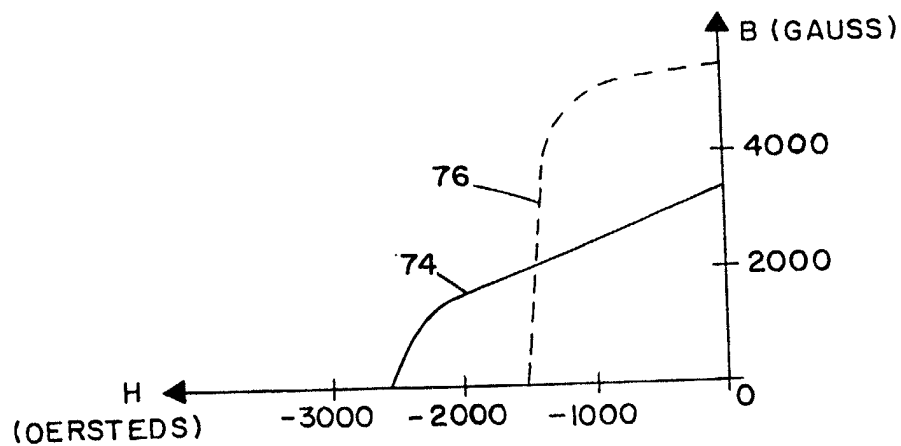


FIG. 7

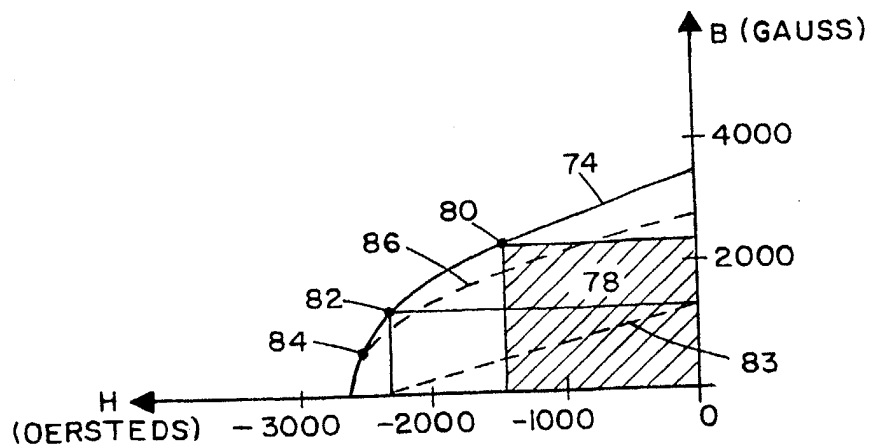
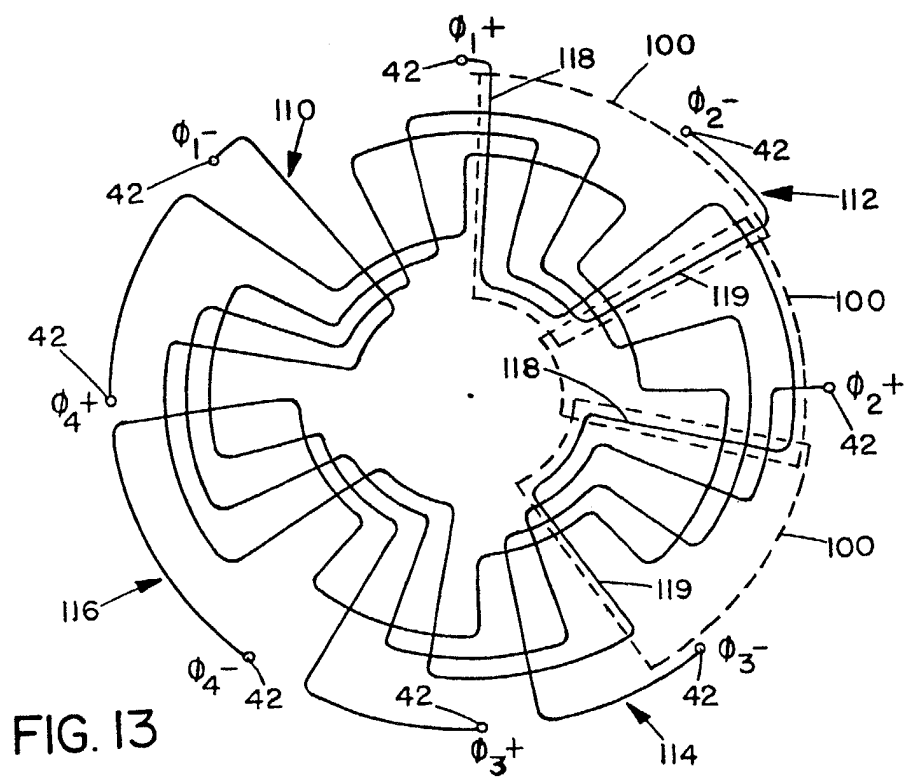
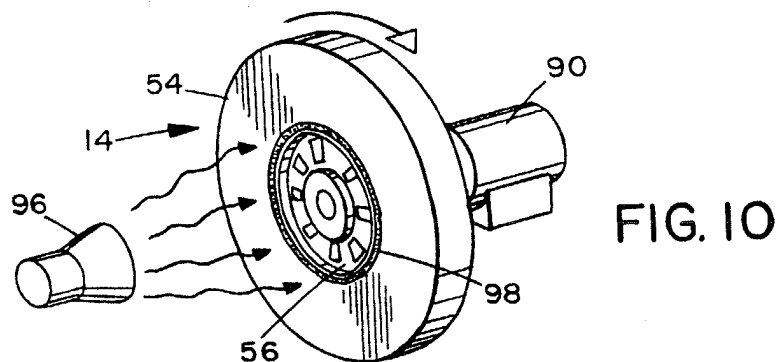
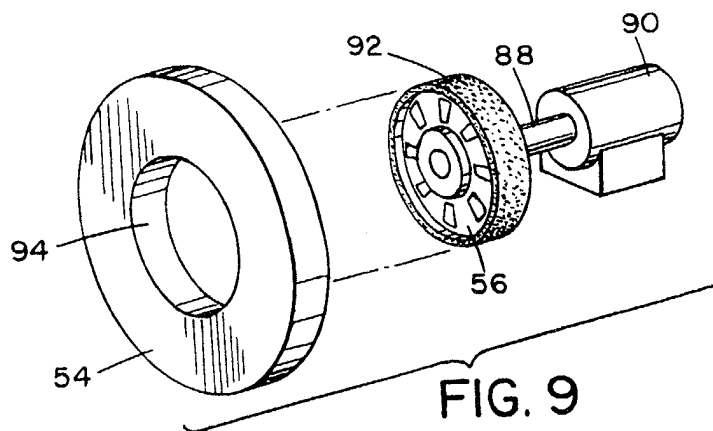


FIG. 8

4/13



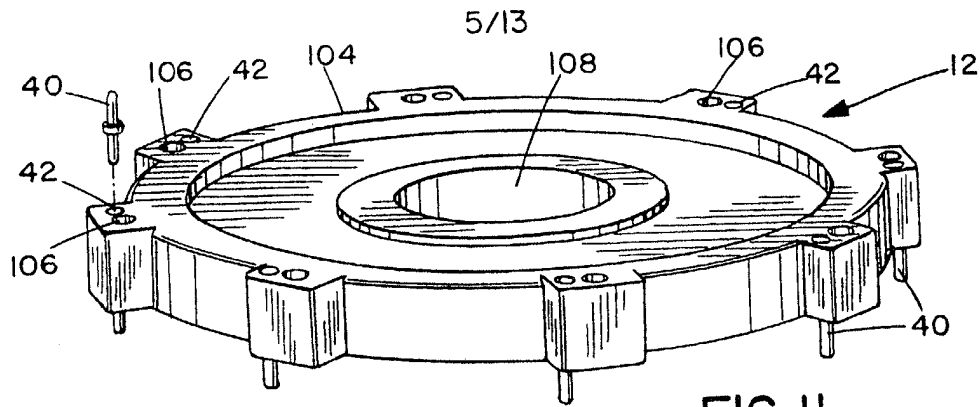


FIG. 11

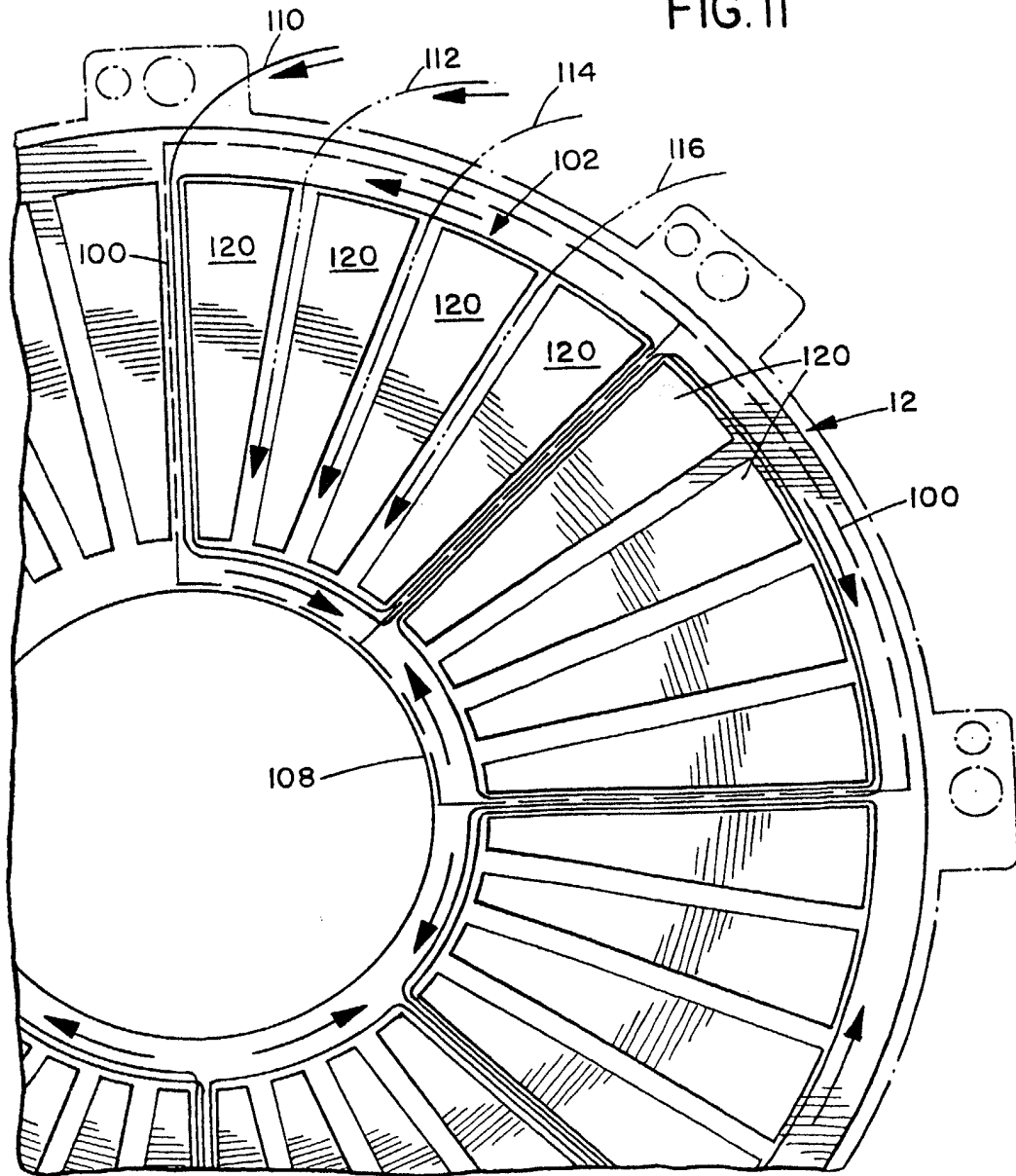


FIG. 12

6/13

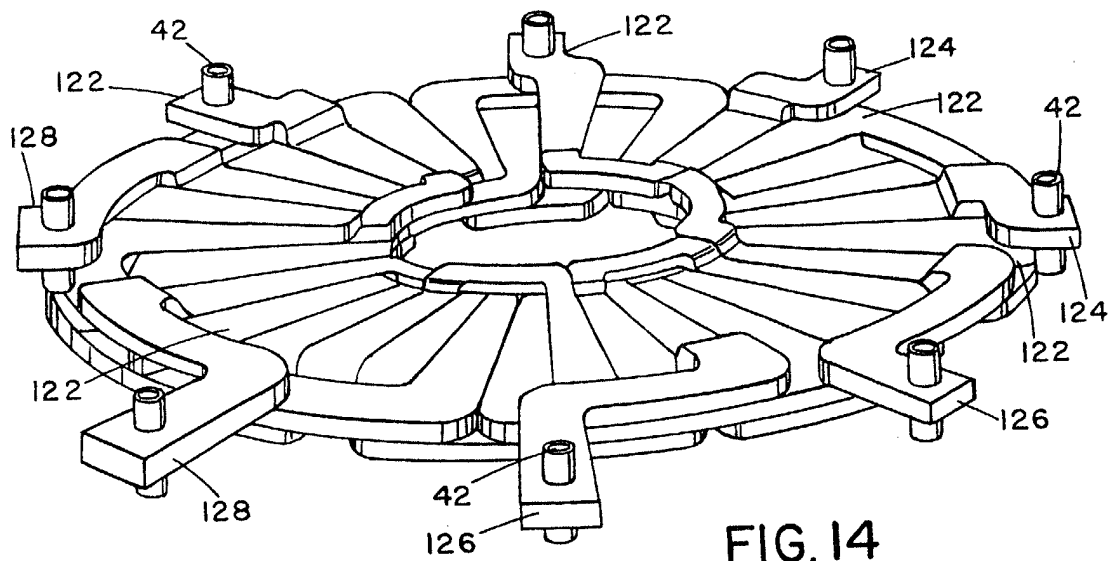


FIG. 14

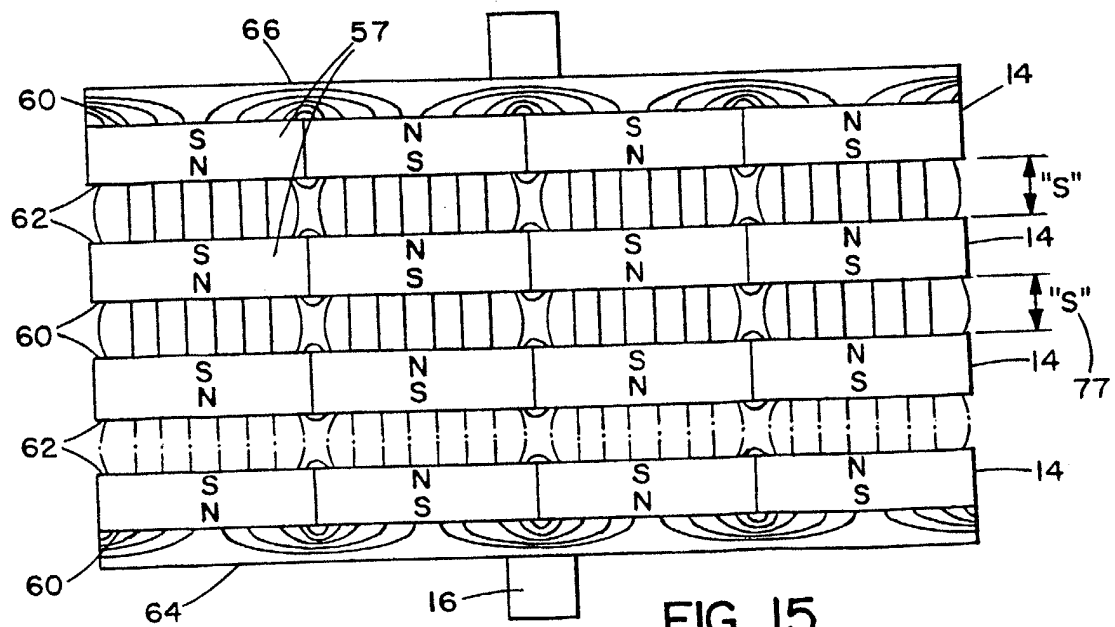


FIG. 15

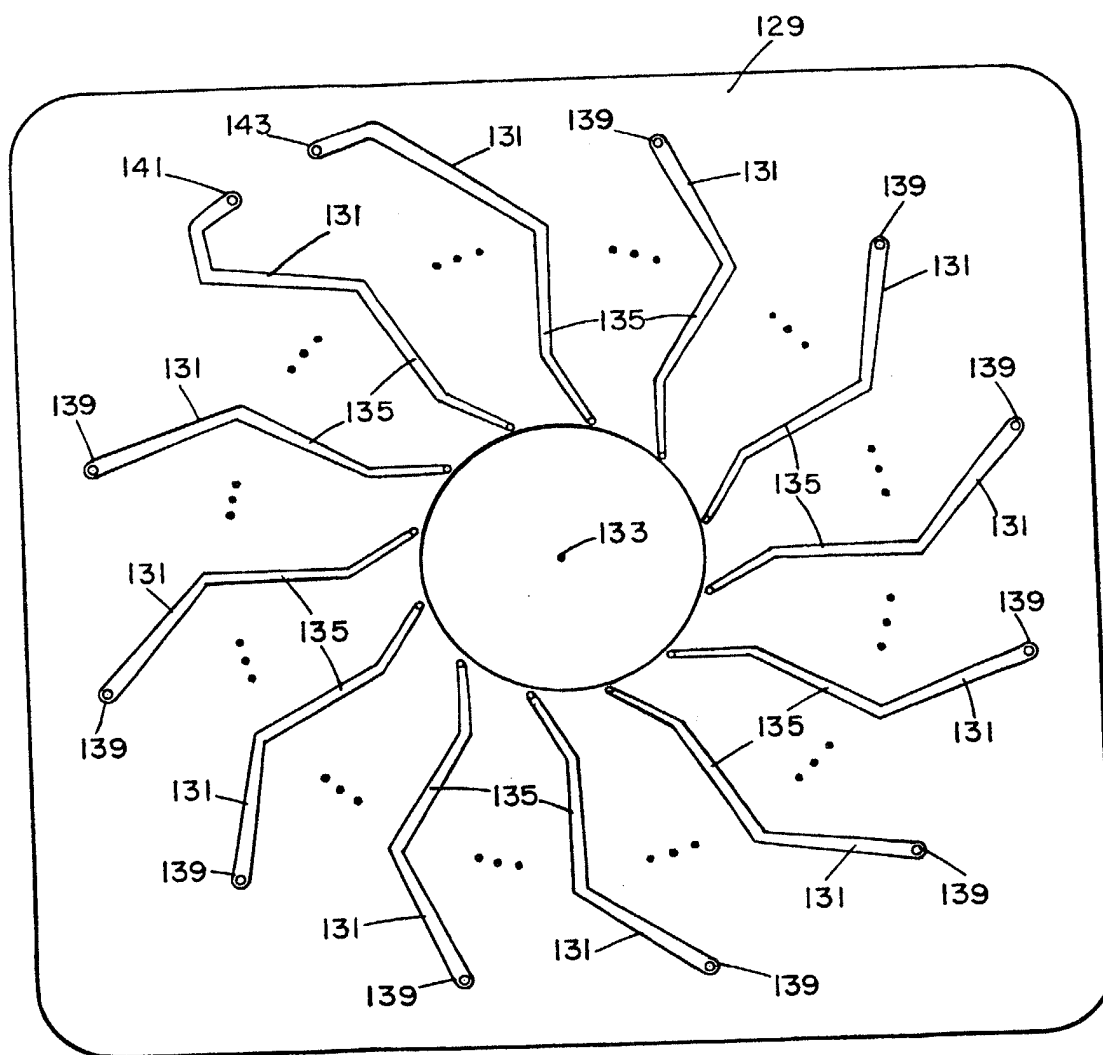
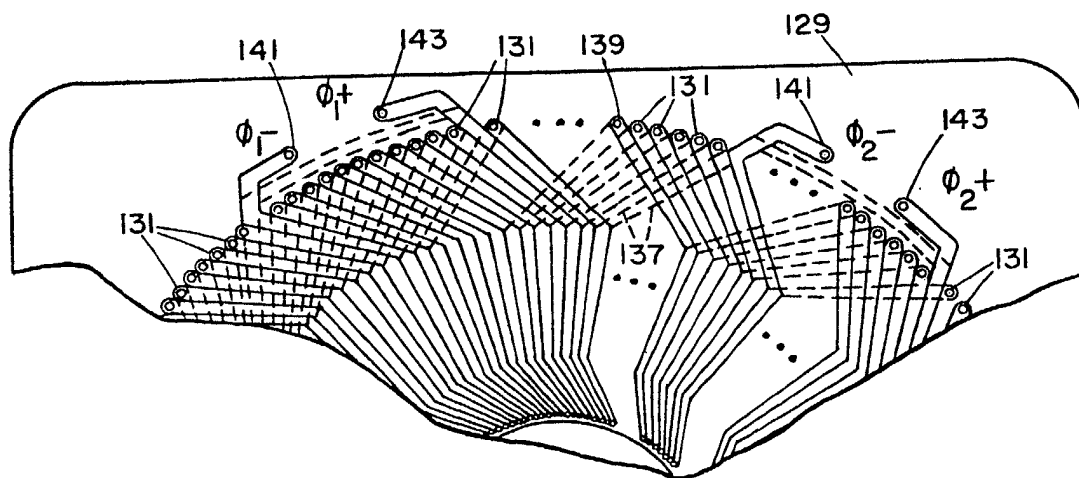
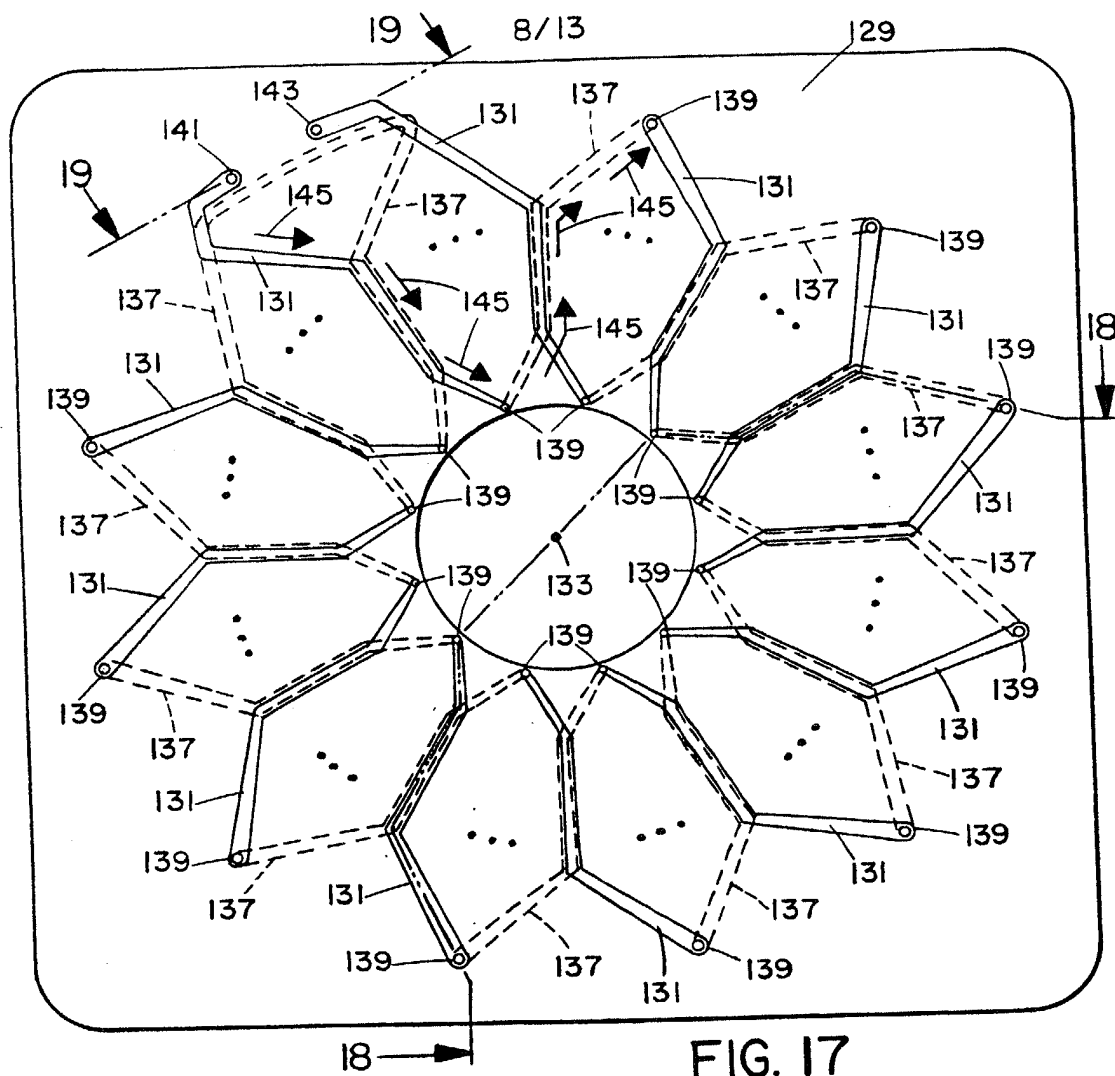


FIG. 16



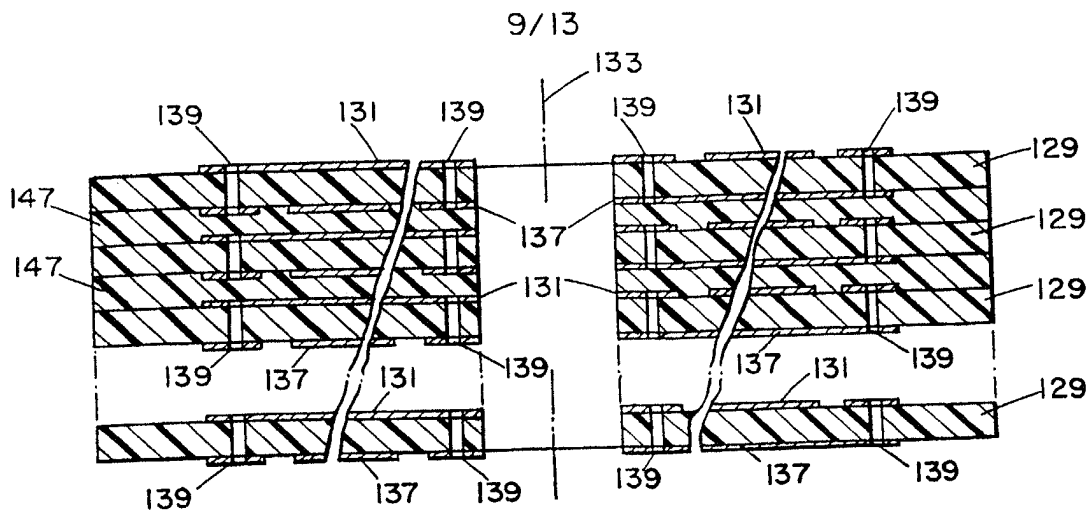


FIG. 18

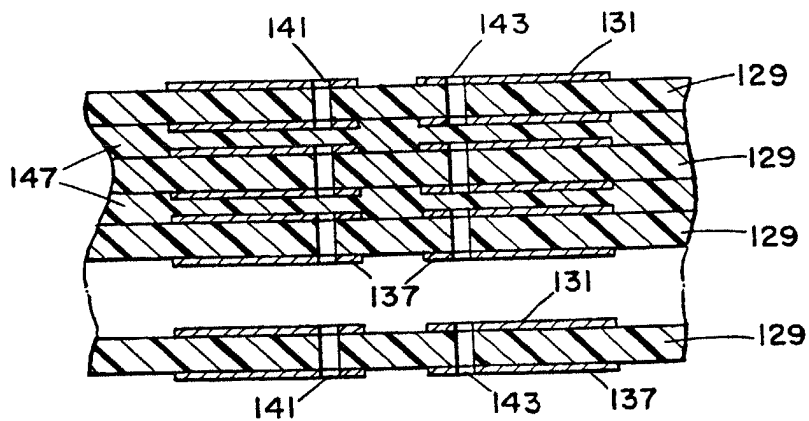


FIG. 19

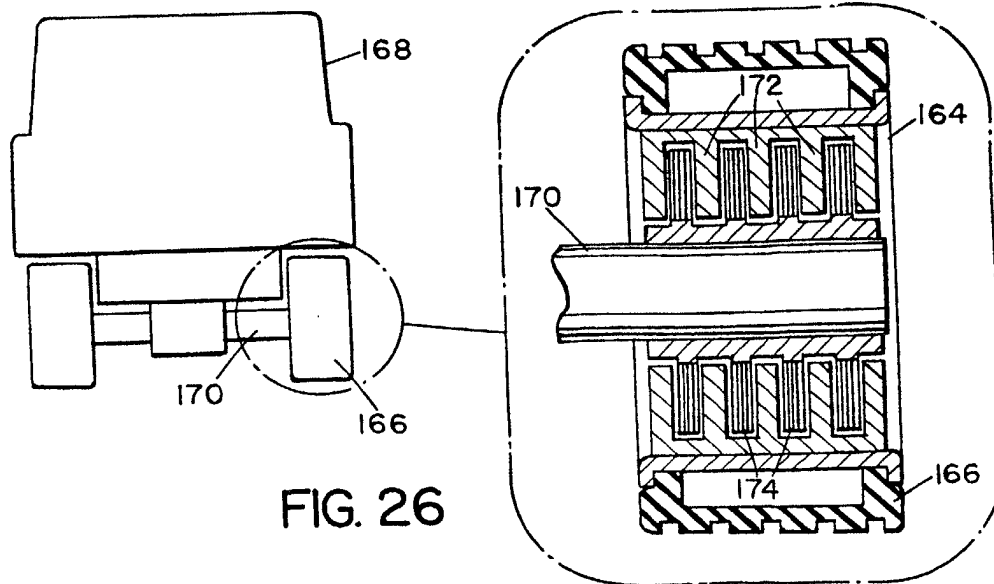


FIG. 26

10/13

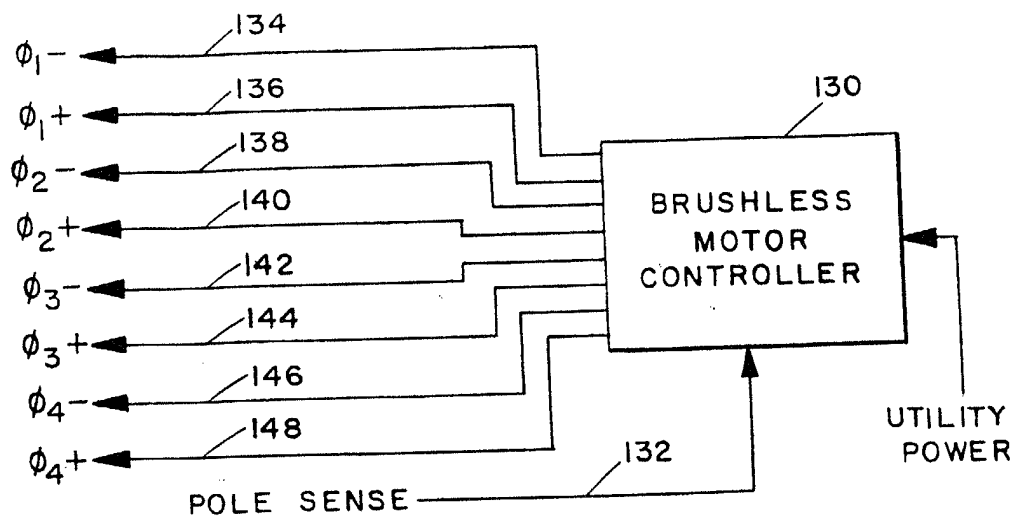


FIG. 21

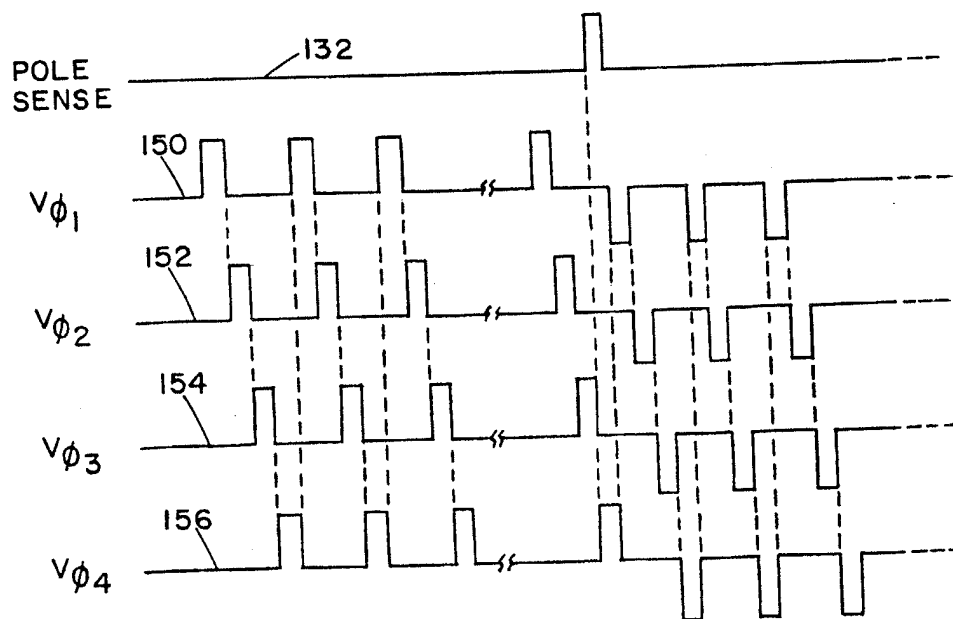


FIG. 22

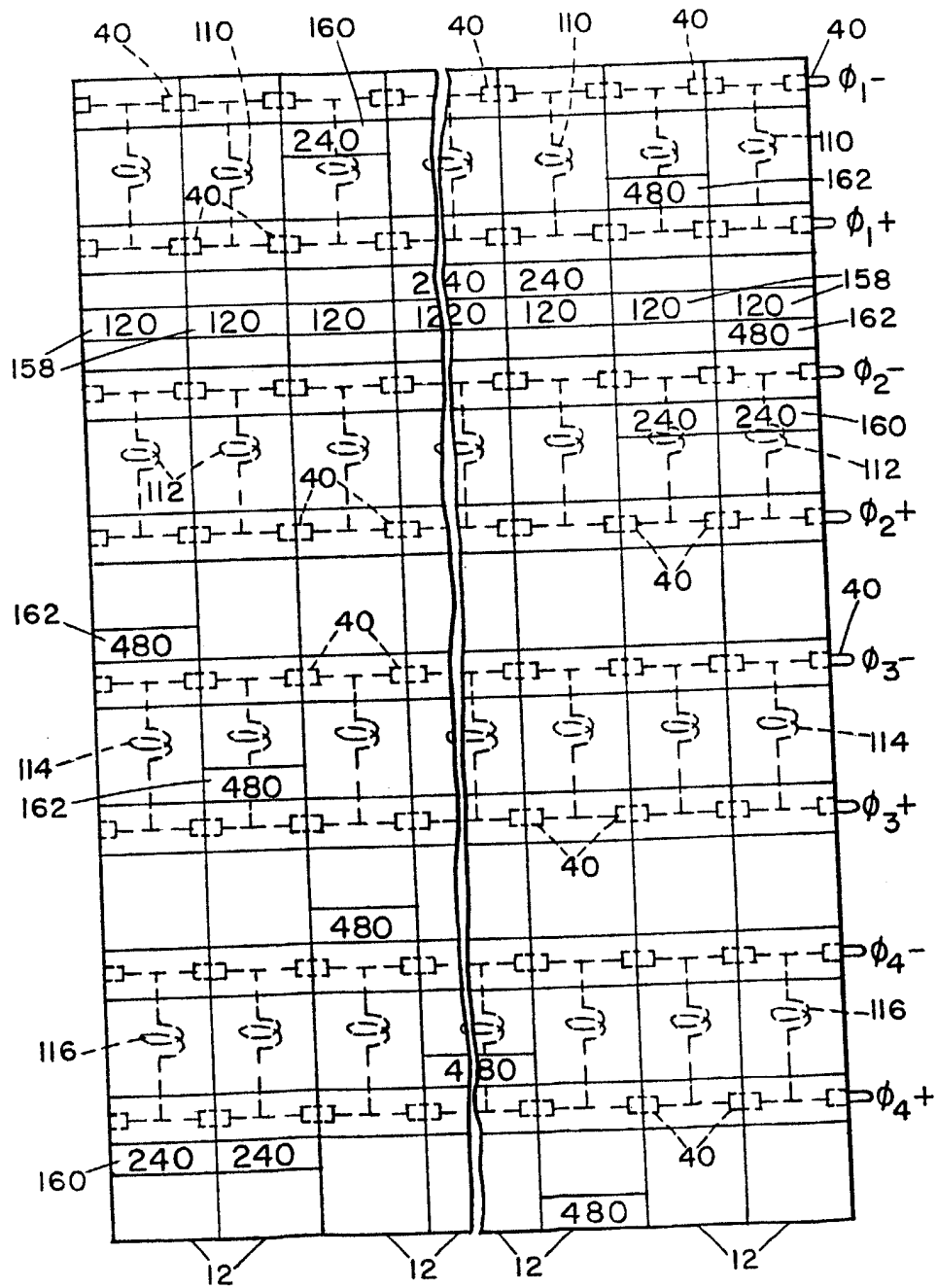


FIG. 23

12/13

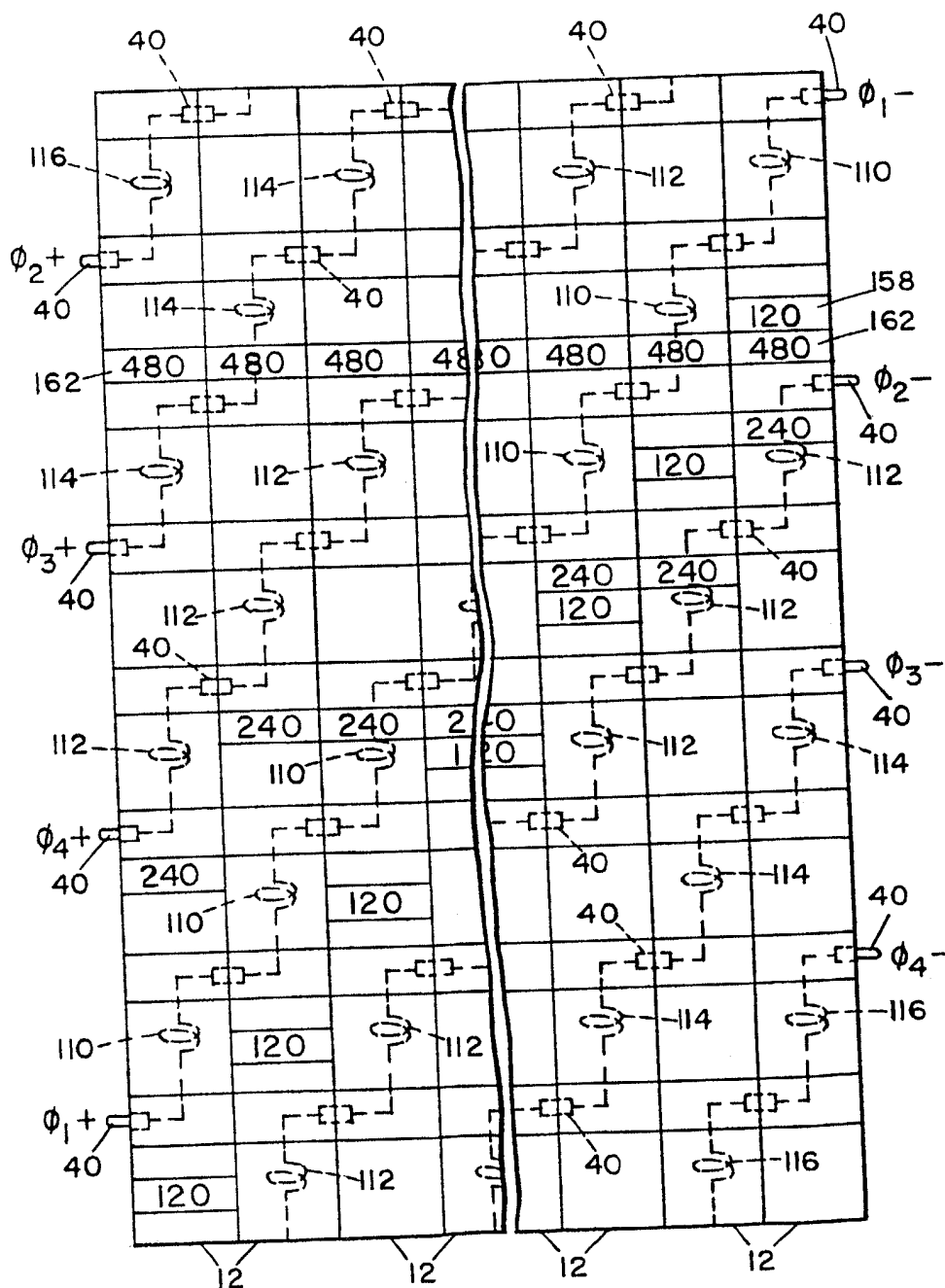


FIG. 24

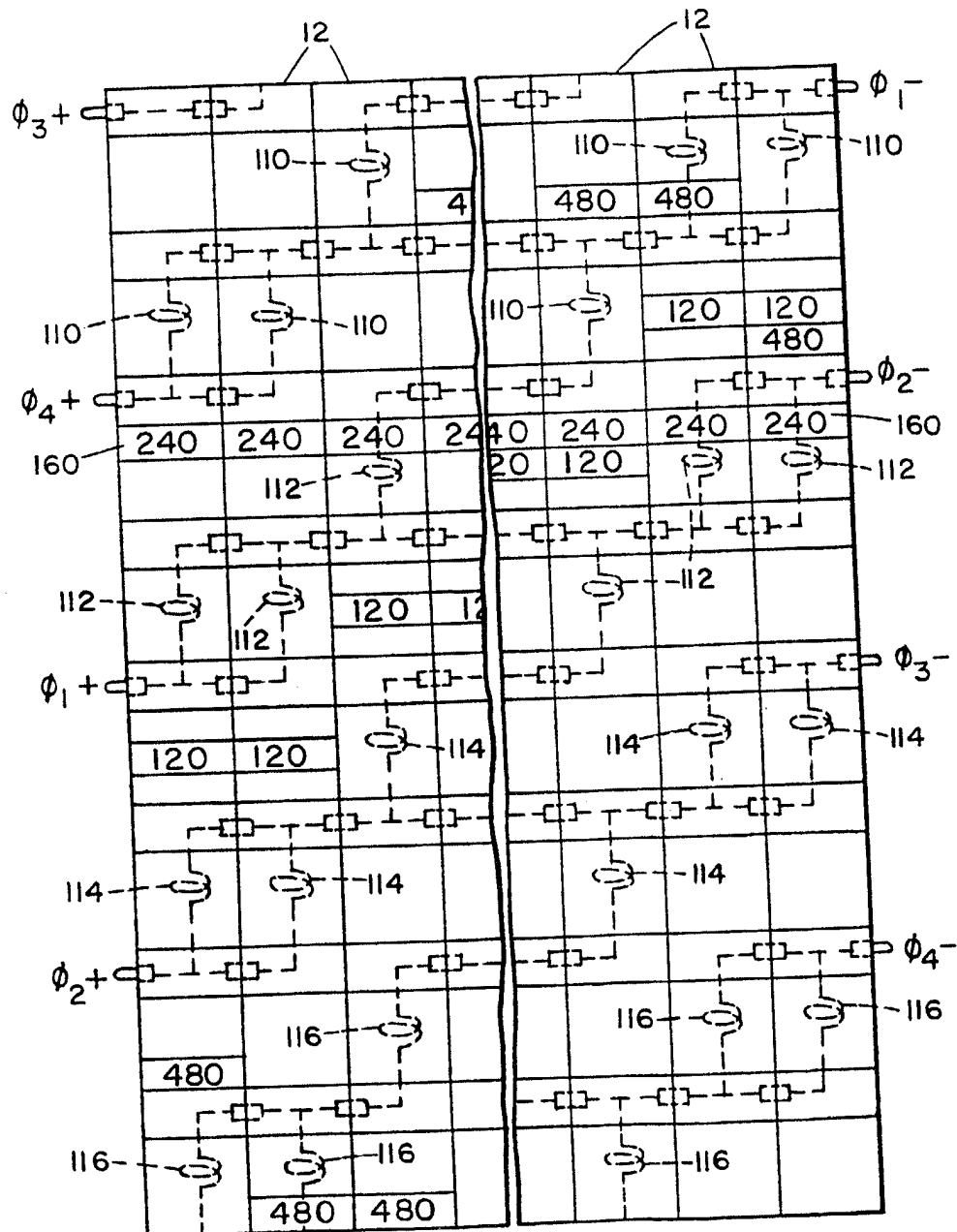


FIG. 25